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REFRACTIVE INDEX OF OPTICAL MATERIALS IN THE INFRARED REGION

A. J. MOSES

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CULVER CITY CALIFORNIA

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ABSTRACT

Refractive index data and some extinction coefficients are provided for the infrared region for the following materials: silicon, germanium, zinc sulfide, cadmium telluride, zinc selenide, silica, calcium fluoride, magnesium fluoride, aluminum oxide, magnesium oxide, aluminum, gold and silver. The dependence of these optical constants on wavelength, temperature, crystal form, film preparation technique, radiation and other factors is included.

This report has been reviewed and is approved for publication.

Sheldon J. Welles

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Electronic Properties Information Center

E. F. Smith

E. F. Smith
Project Manager

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FOREWORD

This report was prepared by Hughes Aircraft Company, Culver City, California, under Contract Number F33615-68-C-1225. The work was administered under the direction of the Air Force Materials Laboratory, Air Force Systems Command, Wright-Patterson Air Force Base, Ohio, with Mr. B. Emrich, Project Engineer.

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INTRODUCTION

These data sheets have been prepared to meet a need for infrared refractive index information on optical materials with emphasis on high temperature utilization. Sources of information for these data sheets include periodicals, reports, proceedings of meetings and vendor literature. In addition to the 40, 000 entries in the EPIC files, non-indexed material was also drawn upon to provide the desired degree of completeness. Inadequate materials characterization and differences in experimental techniques have made it unwise to judge the quality of the data and have resulted in a presentation of most of the data from the literature. In addition to the dependence of the refractive index and extinction coefficient on wavelength, the dependence on crystal form, film preparation techniques, temperature and radiation are considered. The designer will also find optical transmission plots and physical property information to be helpful.

The data sheets are organized in eight chapters comprising a technical introduction, definitions, experimental measurement techniques, problems associated with films, refractive index data for semiconductors, fluorides and ceramics, and metals. For convenience, a conversion table from wave number to wavelength is provided in the Appendix. The bibliography is divided into two parts where the first part lists references in the EPIC system, e.g., McCarthy (26010), and the second part lists non-EPIC references, e.g., Kodak[1967].

Users of the data sheets are encouraged to bring to the author's attention omissions of appropriate data so that supplements will be reasonably complete.

CHAPTER 1
TECHNICAL INTRODUCTION

GENERAL INFORMATION

This report provides a concentration of data for optical constants of thirteen materials with emphasis on the refractive index in the infrared region of the optical spectrum. Considerable extinction coefficient data are also included as an aide to the design engineer. The refractive indices and extinction coefficients are presented as a function of (1) wavelength, (2) temperature, (3) pressure, (4) materials preparation technique and (5) radiation environment.

OPTICAL SPECTRUM

The optical spectrum is illustrated in Figure 1-1. This report emphasizes the infrared region between 0.8 and 1000 microns, though some data for the ultraviolet and visible regions are included.

MATERIALS PROPERTIES

Properties of optical materials are summarized in Table 1-1. This table includes some physical and mechanical properties in addition to optical data and crystal structures because it is realized that the selection of an optical material cannot be based on optical data alone. Transmittance data for the infrared region are included as additional reference material (Figures 1-2 to 1-10). By their nature, cubic crystals have isotropic properties and are therefore preferred for many optical applications. Non-cubic crystals divide incident light into two separate components which travel at different velocities and are consequently refracted to different degrees. This phenomenon is called "double refraction," or, "birefringence." However, crystals that are tetragonal, hexagonal and rhombohedral have one axis along which there is only single refraction. These systems have one optic axis and are called "uniaxial," whereas rhombic, monoclinic and triclinic crystals are biaxial. Crystal classes for optical materials are included in Table 1-1 and are illustrated in Figure 1-11.

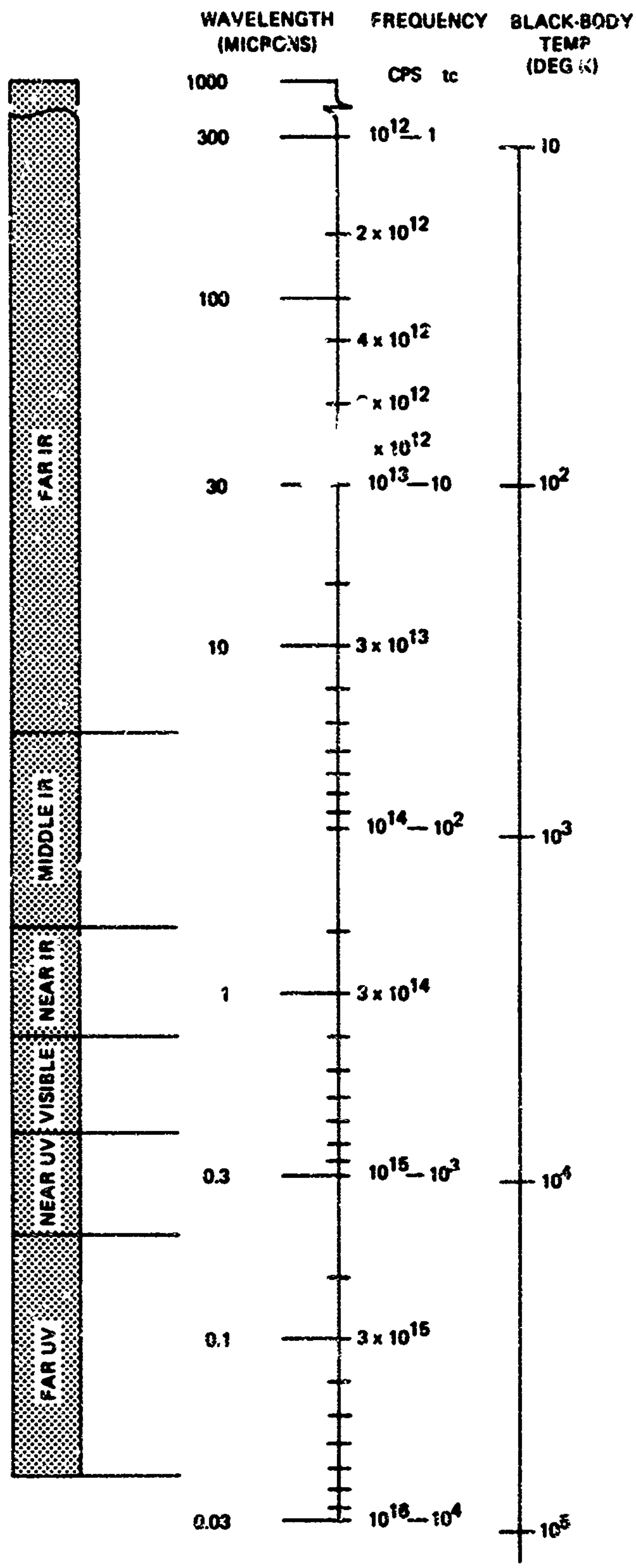

Figure 1-1. Optical Spectrum.

Table 1-1. Properties of Materials for Infrared Optics*

Material	Type of Crystal	Density (g/cm3)	Energy Gap (ev) at 298°K	Refractive Index at ~3μ and 298°K	Useful Upper Transmission limit (μ) (2 mm. thickness, 10% external transmittance)	Youngs' Modulus (10^6 p.s.i.) at 298°K	Hardness Knoop No.	Melting or Softening Point (°K)	Coefficient of Thermal Expansion (10^{-6}/°K)
Germanium	Cubic (diamond)	5.33	0.8	4.037	23	14.9	700-880	1209	5.5
Silica (crystal)	Hexagonal	2.65		1.499	4.5	12.6	741	1743	7.97, 13.37
Silica (fused)		2.20		1.419	4.5	10.6	461	1943	0.55
Sapphire	Hexagonal	3.98	7	1.702	6.5	50.0	1370	2303	6.7
Silicon	Cubic (diamond)	2.33	1.206	3.43	15	19.0	1100-1400	1693	4.7
Aluminum	Face-centered cubic	2.70		3.90		7.06×10^5	25 Brinell	933	23.5
Gold	Face-centered cubic	19.32		2.80		7.8×10^5	28 Brinell	1336	14.1
Silver	Face-centered cubic	10.5		2.00		8.27×10^5	91 Rockwell F	1234	19.1
Magnesium Fluoride	Tetragonal	3.18		1.364	9	16.6	576	1498	11.0
Zinc Sulfide	α form hexagonal cubic	4.09	5.4	2.256	14.5	14	354	1103	6.9
Calcium Fluoride	cubic	3.18		1.418	11.5	14.3	158	1633	20.0
Zinc Selenide	cubic	5.27	4.68	2.440	22	10.3	150	1793	7.7
Magnesium Oxide	cubic	3.58	7.77	1.692	9.5	48.2	692	3073	12.0
Cadmium Telluride	cubic	5.85	1.58	2.695	31	5.3	45	1316	5.9

*Values may depend on selected crystal axis.

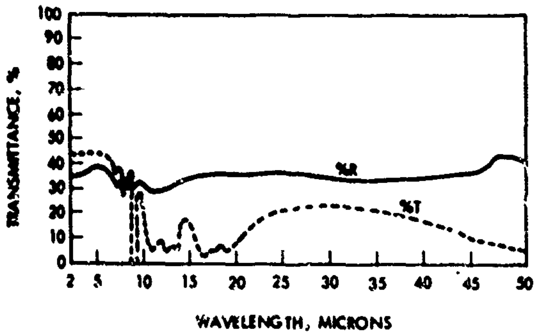

Figure 1-2. Silicon, 1 cm.

Ref. McCarthy (38757)

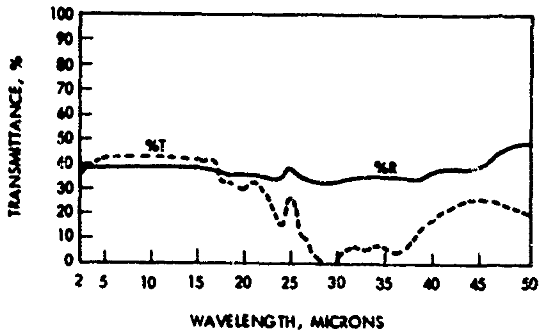

Figure 1-3. Germanium, 1.6 mm.

Ref. McCarthy (38757)

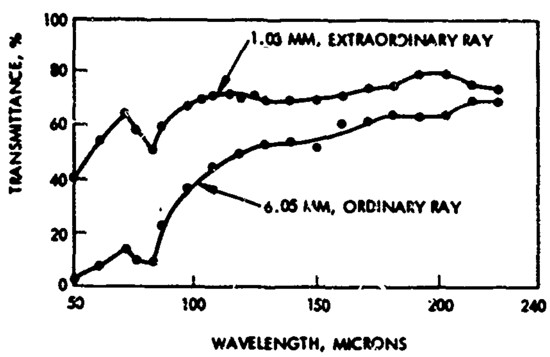

Figure 1-4. Transmission in Far Infrared by Crystalline Silica

Ref. Cartwright [1934]

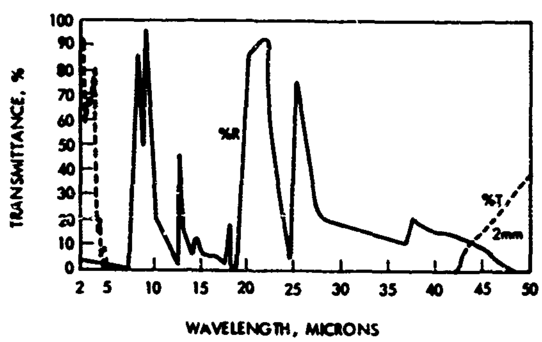

Figure 1-5. Fused Silica, 1 cm.

Ref. McCarthy (38757)

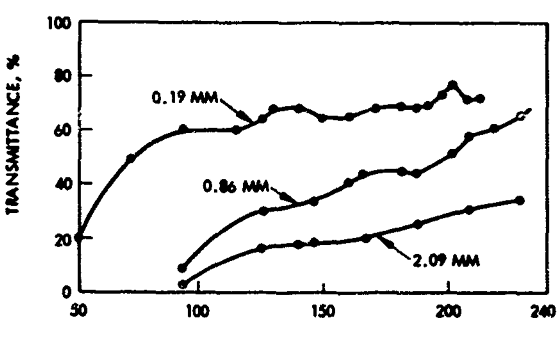

Figure 1-6. Transmission in Far Infrared by Fused Silica

Ref. Cartwright [1934]

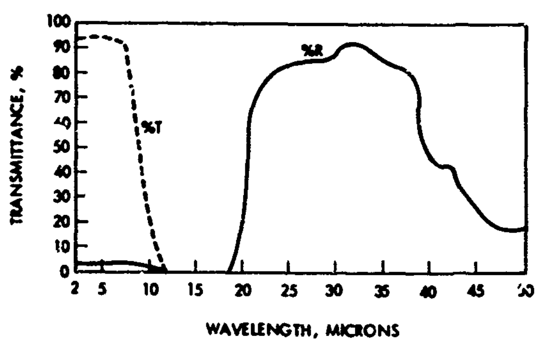

Figure 1-7. Calcium Fluoride, 5 mm.

Ref. McCarthy (38757)

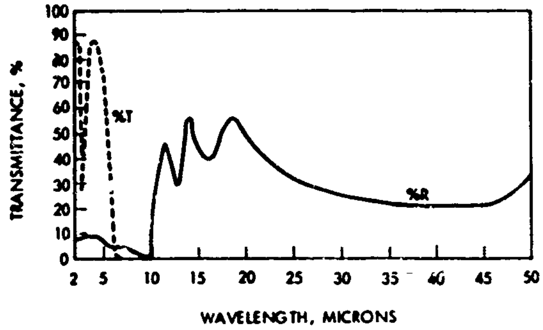

Figure 1-8. Aluminum Oxide — Sapphire, 2 mm.

Ref. McCarthy (26010)

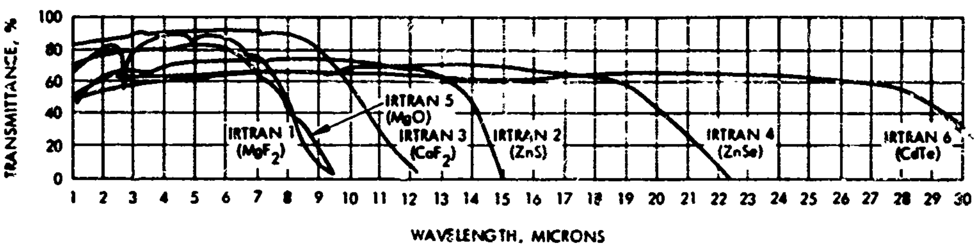

Figure 1-9. Transmission for 2mm Thick Polycrystalline Irtran Samples

Ref. Kodak [1967]

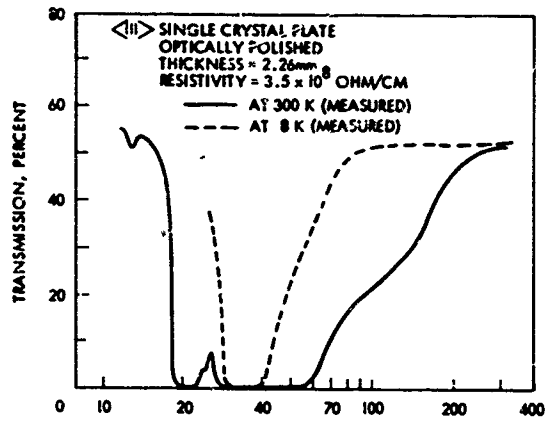

Figure 1-10. Far Infrared Transmission of high resistivity CdTe at 300 K and 8 K

Ref. Johnson, et al [40781]

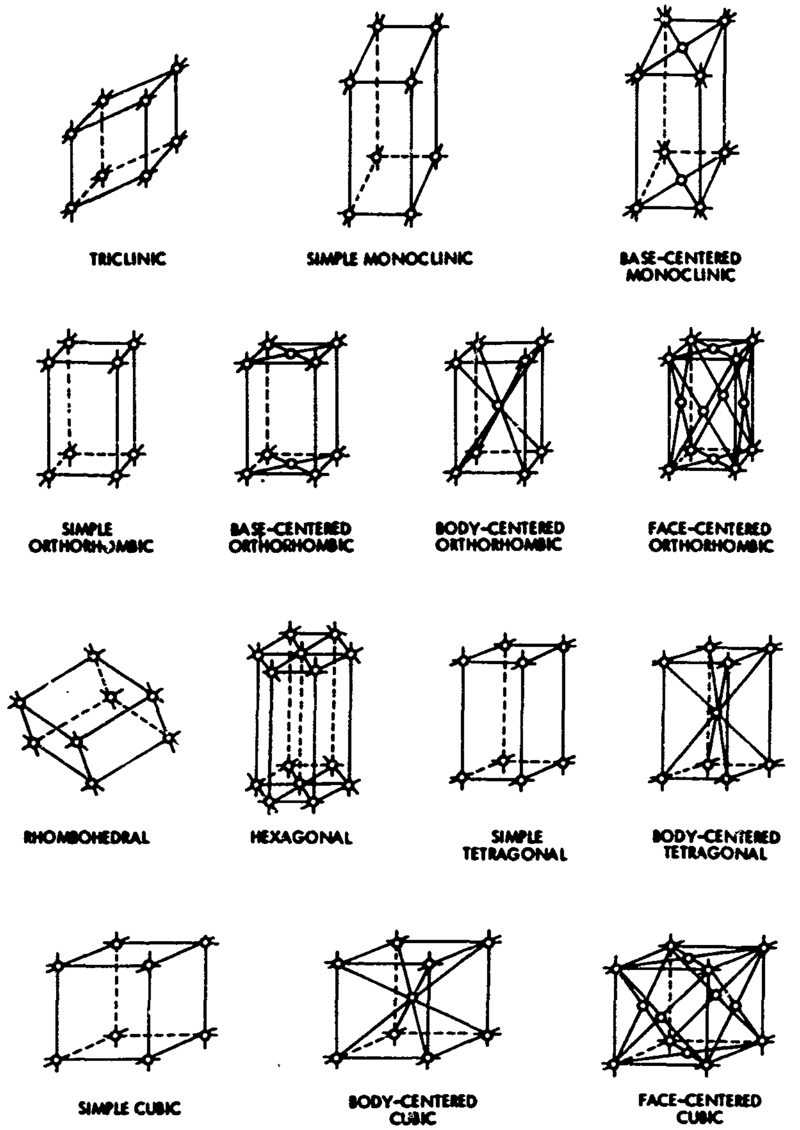

Figure 1-11. Crystal Systems.

CHAPTER 2

DEFINITIONS OF REFRACTIVE INDEX AND FACTORS AFFECTING THE REFRACTIVE INDEX

DEFINITIONS

The refractive index (n) of a material is defined as the ratio of the phase velocity (c) of electromagnetic radiation in vacuum to the phase velocity (v) of the same radiation in the material, or:

$$n = c/v$$

However, since the index of refraction of air is only about 1.0003, it is frequently measured with respect to air instead of vacuum and no correction made for air.

In non-absorbing media, the refractive index is real, while in absorbing media a complex index of refraction (N) is sometimes used. The complex index of refraction is frequently defined as:

$$N = n + ik$$

where k = extinction coefficient or absorption index and $i = \sqrt{-1}$. Both n and k are frequency-dependent.

The real and imaginary parts of the square of the complex refractive index satisfy the Kramers-Kronig relations, as follows:

$$N^2 = (n + ik)^2 = (n^2 - k^2) + 2\,nki$$

$$n^2(\omega) - k^2(\omega) = \frac{2}{\pi} \int_0^\infty \frac{\omega' 2n(\omega')k(\omega')d\omega'}{\omega'^2 - \omega^2} + \text{constant}$$

$$2n(\omega)k(\omega) = \frac{-2\omega}{\pi} \int_0^\infty \frac{n^2(\omega') - k^2(\omega')\, d\omega'}{\omega'^2 - \omega^2}$$

This is, if the absorption index as a function of frequency is known, both $n(\omega)$ and $k(\omega)$ can be evaluated separately.

Optically anisotropic materials divide incident light into two components (double refraction) which are refracted along two mutually perpendicular planes. The ordinary wave travels at a velocity that is independent of the direction of propagation. The extraordinary wave travels at a velocity that is dependent on the relation between its direction and the optic axis. Single refraction occurs for light that travels parallel to the optic axis. The refractive index for the ordinary wave bears the symbol n_o, while n_e denotes the extraordinary wave. Both n_o and n_e are dependent on frequency. Most types of crystals are anisotropic, giving rise to both n_o and n_e. Cubic crystals have refractive indices that are identical in all directions (isotropic) for which reason they are often used in optical instruments.

In this compilation, emphasis is placed on the refractive index for the ordinary wave and for simplicity the corresponding refractive index is denoted by the symbol "n".

DEPENDENCE ON WAVELENGTH

The refractive index of optical materials is dependent on the wavelength of the incident light, as shown for the ordinary refractive index of such materials in Figure 2-1. The refractive indices in Figure 2-1 range from about 1.3 to greater than 33, with glasses in the region between 1.3 and 2.0, semiconductors between 3.4 and 4.1, and metals as high as 33.

The slope of curves from Figure 2-2, $dn/d\lambda$, represents the dispersion and the wavelength-dependence of dispersion is evident from Figure 2-2.

DEPENDENCE ON TEMPERATURE

The temperature coefficient of the refractive index is at least in part affected by the thermal expansion of the optical material, as shown by an approximate 10 percent contribution to the temperature coefficient of the refractive index for germanium [Ref. Cardona (2569).]

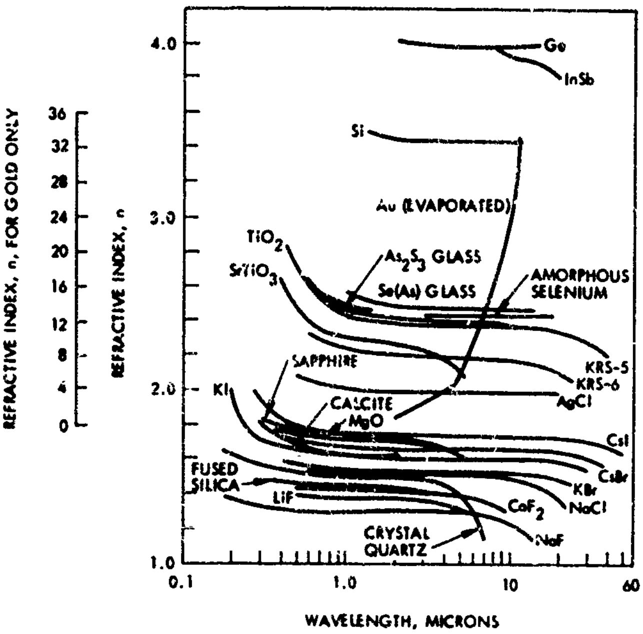

Figure 2-1. The refractive indices of selected optical materials.

Ref. Ballard (12539)

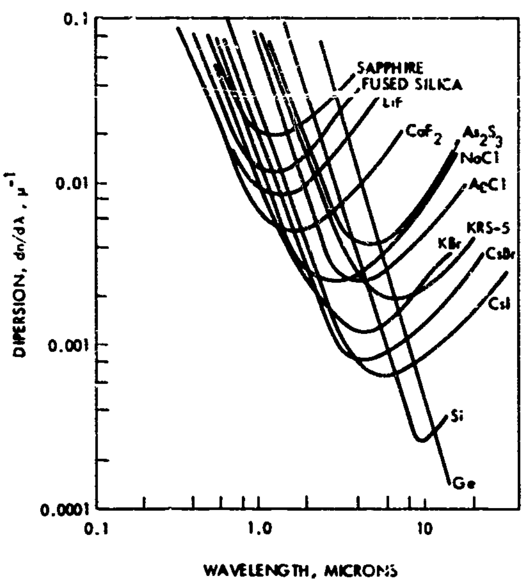

Figure 2-2. Dispersion for selected materials.

Ref. Wolfe [1965]

Heating a material causes a change in its dimensions. This change in dimensions is expressed by the linear coefficient of thermal expansion. In most cases, this coeff'cient is positive, increasing with rising temperature. The coefficient is usually small for optical materials, as may be seen from Table 1-1 and is wavelength-dependent (Figure 2-3). The occurrence of phase changes in the material can cause a major change in the coefficient of thermal expansion. For anisotropic crystals, the thermal expansion is also influenced by the direction of the heat flow. The correlation betw en refractive index, thermal change in refractive index, and linear thermal coefficient of thermal expansion for selected optical materials is demonstrated in Figure 2-4.

DEPENDENCE ON PRESSURE

Application of external pressure on a material affects the material's refractive index in excess of changes attributable to compressibility and is explained by the existence of two effects due to pressure: (1) change in electron density and (2) change in electronic polarizability; the first effect produces an increase in refractive index with pressure, while the second effect reduces it. No wavelength-

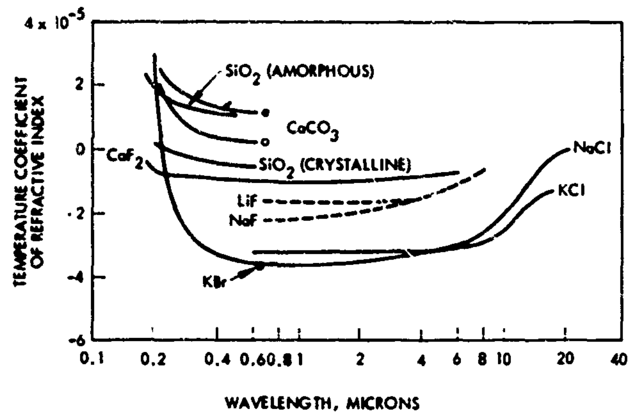

Figure 2-3. Temperature Coefficient of Refractive Index for Some Optical Materials

Ref. Smakula [1952]

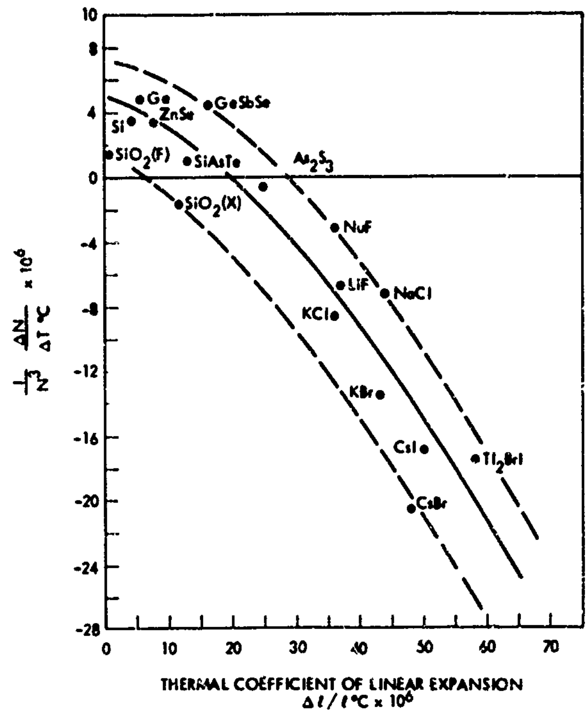

Figure 2-4. Correlation of refractive Index, Thermal Change in Refractive Index, and Linear Thermal Coefficient of Expansion for IR Optical Materials

Ref. Hilton Jones [1967]

dependence of the pressure coefficient of the refractive index is expected, at least in the near infrared region [(Ref. Cardona (2569)].

DEPENDENCE ON NUCLEAR RADIATION

Nuclear radiation of space and laboratory origin can affect the refractive index of an optical material. Most of the studies involving radiation effects on the refractive index have been made on glasses. In this report, emphasis is placed on radiation effects to fused quartz since this material finds wide use on spacecraft as a window material.

DEPENDENCE ON MATERIALS PREPARATION TECHNIQUE

The refractive index of a material is a function of the surface condition and chemical composition. In the case of evaporated films, the refractive index is also influenced by: evaporation atmosphere, substrate temperature, substrate material and orientation, condensation rate, film thickness and source temperature.

CHAPTER 3
METHODS FOR DETERMINING THE REFRACTIVE INDEX

Widely used methods for determining the refractive index of a material are based on the following principles:

1. Deviation
2. Reflection
3. Interference
4. Transmission

Fundamentals of these methods will be discussed in this chapter. Data tables in this report indicate which method was used to determine refractive indices.

DEVIATION

Deviation methods, measuring the deviation of a beam of light from a known path, can be considered to be the classical approach.

Deviation methods use a prism and therefore cannot be used for films. A typical deviation method is the prism deviation method, where the light is refracted through the prism at a given deviation which need not be the minimum deviation. Figure 3-1 illustrates the geometry of the prism, which permits calcuation of the refractive index as shown below. [Ref. Wolfe, et al (26316)].

$$\theta'_1 + \theta'_2 = \alpha$$

Snell's law provides the next pair of equations:

$$n_1 \sin \theta_1 = n_2 \sin \theta'_1$$

$$n_1 \sin \theta_2 = n_2 \sin \theta'_2$$

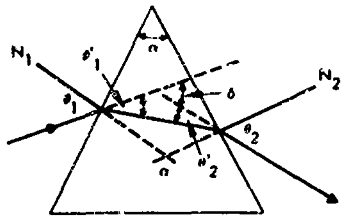

Figure 3-1. Prism Geometry
for Minimum and Normal
Deviation

Now a series of substitutions puts these equations in a form that simplifies solution of n_2/n_1:

$$n_1 \sin \theta_1 = n_2 \sin (\alpha - \theta'_2)$$

$$= n_2 (\sin \alpha \cos \theta'_2 - \cos \alpha \sin \theta'_2)$$

$$= n_2 \left[\sin \alpha (1 - \sin^2 \theta'_2)^{1/2} - \cos \alpha \sin \theta'_2\right]$$

$$\sin \theta'_2 = \frac{n_1}{n_2} \sin \theta_2$$

$$\sin \theta_1 = \sin \alpha \left[(n_2/n_1)^2 - \sin^2 \theta_2\right]^{1/2} - \cos \alpha \sin \theta_2$$

$$(n_2/n_1)^2 = \sin^2 \theta_2 + \frac{\sin^2 \theta_1 + 2 \sin \theta_1 \cos \alpha \sin \theta_2 + \cos^2 \alpha \sin \theta_2}{\sin^2 \alpha}$$

$$(n_2/n_1)^2 = \frac{\sin^2 \theta_2 + \sin^2 \theta_1 + \sin \theta_1 \cos \alpha \sin \theta_2}{\sin^2 \alpha}$$

$$n_2 = \frac{n_1}{\sin \alpha} (\sin^2 \theta_1 + \sin^2 \theta_2 + 2 \sin \theta_1 \sin \theta_2 \cos \alpha)^{1/2}$$

REFLECTION

Reflection methods for determining optical constants are based on measurement of the reflection coefficient and the phase relationship between the two components of the reflected radiation, where one component is perpendicular to and the other component is parallel to the plane of incidence, as shown in Figure 3-2. In some reflection methods, both reflectivity and transmission must be measured but the data then permit the calculation of refractive index and extinction coefficient [Ref. Spitzer and Fan (791)].

A detailed description of a reflection method has been provided by Avery [Ref. Avery [1952]]. Avery's method briefly entails:

1. Determination of the ratio of the reflection coefficients (ρ^2) for incident light polarized in and perpendicular to the plane of incidence.
2. Let the complex refractive index be $N = n(1 - ik)$, then at the angle of incidence :

$$\rho^2 = \frac{a^2 + b^2 - 2a \sin\theta \tan\theta + \sin^2\theta \tan^2\theta}{a^2 + b^2 + 2a \sin\theta \tan\theta + \sin^2\theta \tan^2\theta}$$

where

$$N^2 - \sin^2\theta = (a - ib)^2$$

3. From curves relating ρ^2 to n and k for a number of angles of incidence, and measurements at two or more angles of incidence, n and k can be determined.

INTERFERENCE

In principle, interferometric methods are based on dividing the light output of a source into two or more beams which are then superimposed. By illumination of parallel plates of a transparent material with these superimposed beams, reflection from the upper and lower

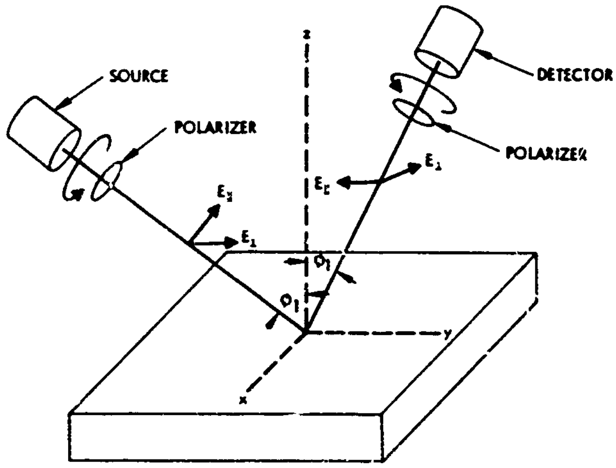

Figure 3-2. Geometry for the Reflection Method

Ref. Wolfe, et al, (26316)

surfaces will occur and an interference pattern will be created. [Ref. Wolfe, at al (26316)].

The Variable Angle Monochromatic Fringe observation (VAMFO) method represents an interferometric method for determining the thickness and refractive index of transparent films on reflective substrates using the apparatus depicted in Figure 3-3 [Ref. Pliskin & Fan (36787)]. The technique employs a rotating stage which is attached to an xy stage. Maxima and minima (fringes) are observed as the stage and samples are rotated, providing the number of fringes between angular limits. A microscope provides magnification. The refractive index is given by the equation.

$$n = \frac{\Delta m \lambda}{2t\,(\cos\theta_2 - \cos\theta_1)}$$

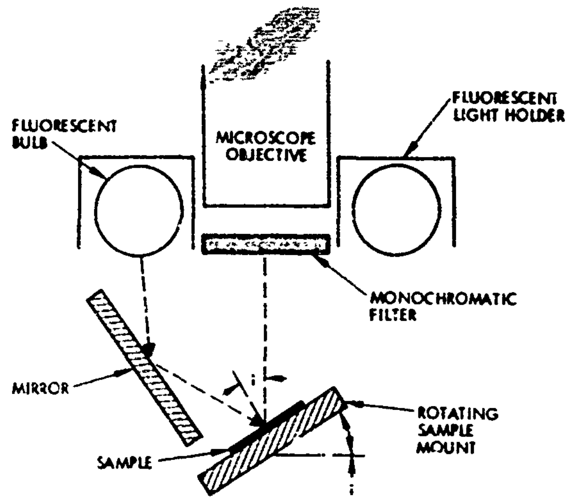

Figure 3-3. Diagram of VAMFO Apparatus

Ref. Pilskin and Fan (36787)

where

Δm = number of fringes observed between refraction angles θ_1 and θ_2,

t = film thickness

λ = wavelength of filtered light

TRANSMISSION

The transmission method for determining the refractive index of films is based on the following equations:

$$2nt = m\lambda \text{ for maximum transmission}$$

and

$$2nt = (m + \tfrac{1}{2})\lambda \text{ for minimum transmission,}$$

where

t = film thickness

λ = wavelength of incident light

m = the order number

The order number can be determined by using the first equation in the region of minimum dispersion, where the order number is low and the product 2nt is essentially constant. The film thickness is measured by other tests. [Ref. Wales, et al., (31497)].

CHAPTER 4
PROBLEMS ASSOCIATED WITH FILMS

The optical characteristics of films are sensitive to the film microstructure, which in turn is affected by various deposition parameters. The formed film is subject to aging effects including oxidation, recrystallization, hydrolysis, thermal decomposition, chemical reactions with the environment, and other causes. As a result of these factors, optical data for films often show a wide spread in values between observers.

Optical films are most commonly deposited by thermal evaporation in a vacuum onto a substrate that may be heated. Factors influencing the optical characteristics of evaporated films include the following:

1. Condensation rate
2. Source temperature
3. Substrate material
4. Substrate temperature
5. Ambient pressure
6. Nature of ambient environment
7. Film thickness.

Specific results showing the effects of these factors on the refractive index are presented on appropriate materials data sheets in this report. Some additional remarks relating to these factors serve to demonstrate the strong influence of some of the factors.

The presence of hydroxyl groups, usually formed by the reaction of water vapor with the material, causes an absorption band near 2.7 microns and a low refractive index at that wavelength. This phenomenon is most marked in sputtered, anodized, and electrodeposited films.

An example of aging is the growth of natural oxide on aluminum, which has been reported to reach a maximum thickness of 45 Angstroms in one month. Oxides usually have a different refractive index from that of the matrix, as is illustrated in Table 4-1, where germanium, silicon, aluminum and their oxides are compared.

Table 4-1. Comparison of Refractive Indices of Elements and Oxides

Material	Wavelength, (microns)	Refractive Index (n)
Germanium	not stated	4.0
Germanium Oxide (GeO_2)		
(hexagonal)	not stated	1.735
(tetragonal)	not stated	2.05 - 2.10
Silicon	0.55	0.055
Silicon monoxide (SiO)	0.55	1.9 - 2.0
Silicon sesquioxide (Si_2O_3)	0.55	1.52 - 1.55
Silicon dioxide	0.55	1.46 - 1.47
Aluminum	2.0	2.3
Aluminum oxide (Al_2O_3)	2.0	1.74

The effect of surface oxide in metal deposition is particularly apparent where extremely thin films are laid down. Such ultra-thin films may act as getters for oxygen and other gases. On the other hand, the reducing property of a hydrogen atmosphere during evaporation can lead to a refractive index, representative of the pure element (e.g., germanium) because the hydrogen ties down the oxygen chemically. High substrate temperatures can cause a large reduction in refractive index by formation of a relatively thick oxide layer, as was demonstrated for germium by Davey, et al. [Ref. Davey at al., (13363)]. Even this short discussion of problems associated with films should convince the reader that published optical data for films should be used with caution.

CHAPTER 5

REFRACTIVE INDEX DATA FOR SEMICONDUCTORS

Electrons in crystals are located within energy bands, shown in Figure 5-1, and the bands are separated by regions for which no electron energy states are permitted; these regions are called "band gaps" or "energy gaps." In conductors, one or more of the bands are partially filled. In semiconductors, all bands are completely filled, except for one or two partially filled bands. Insulators possess allowed energy bands that are either empty or filled with no electrons available for movement in an electric field.

The distinction among conductors, semiconductors and insulators is of course not as sharply drawn as the preceding discussion might imply. Electrical resistivity measurements, summarized in Figure 5-2, show the wide range in resistivity between good conductors and good insulators. Figure 5-2 also shows the wide range within a class (e. g., insulators) and the effect of impurities on the electrical resistivity of semiconductors (germanium).

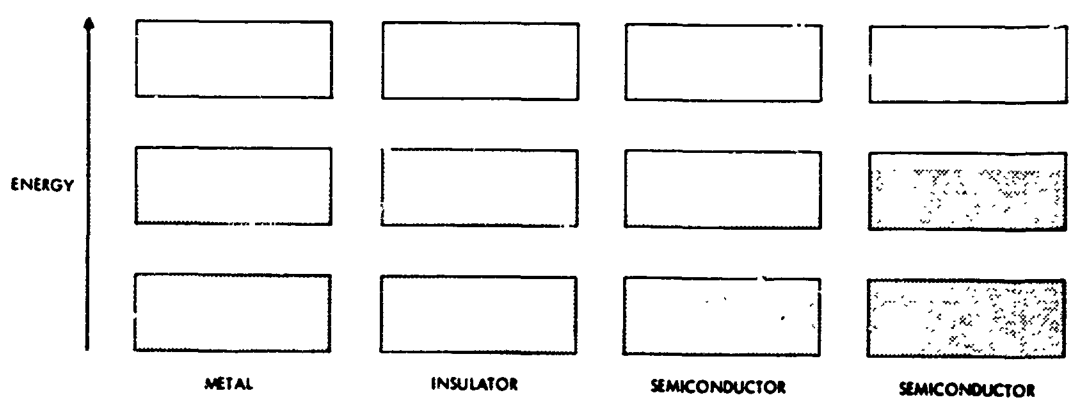

Figure 5-1. Schematic Electron Occupancy of Allowed Energy Bands for an Insulator, Metal, and Two Semiconductors. The Vertical Extent of the Boxes Indicates the Allowed Energy Regions; The Shaded Areas Indicate the Region Filled With Electrons

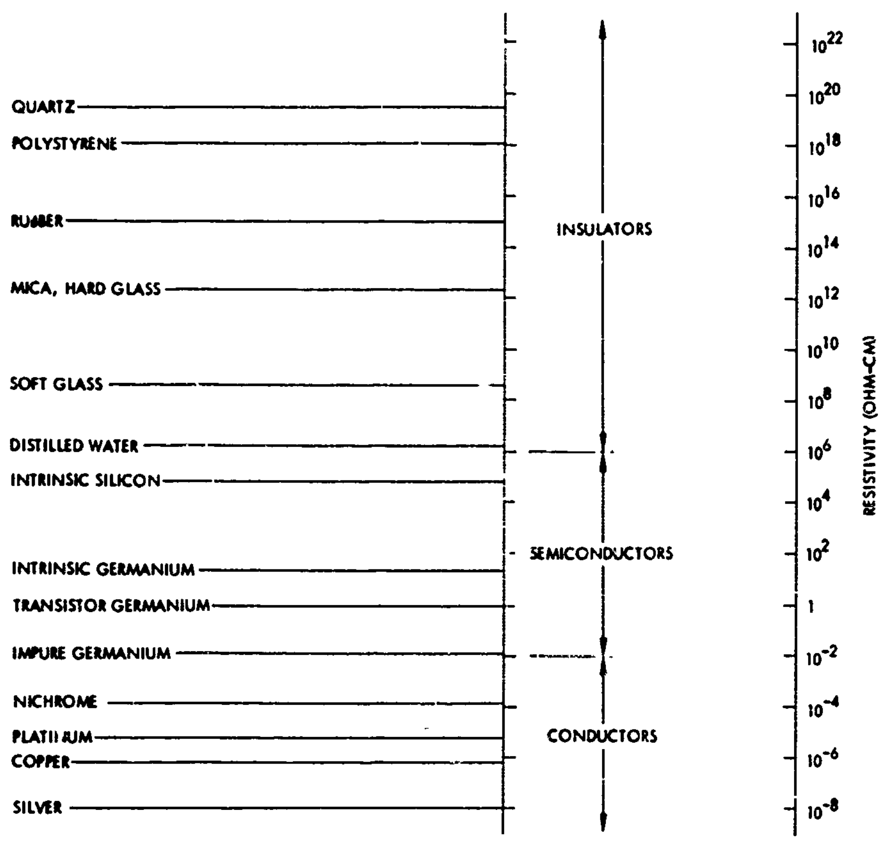

Figure 5-2. Electrical Resistivity of Materials

SILICON

INTRODUCTION

Silicon is a semiconductor that has found application in infrared optics, transistors, diodes, rectifiers, solar cells, alloys and as deoxidizer in steels. Silicon is the second most abundant element, usually occurring as oxide or silicate. Recovery from the oxide is accomplished by reduction with carbon. Purification is accomplished by distillation of silicon tetrachloride with subsequent reduction of the tetrachloride with zinc. Zone melting with solidification and growth of single crystals from the molten state provide further purification. Highly purified silicon has a resistivity of approximately 2.5×10^5 ohm-cm.

The physical properties of intrinsic silicon were summarized in Table 1-1. Impurities in silicon have an effect on a number of properties including electrical resistivity and optical transmission. It is therefore important to realize that differences in optical data of several authors may arise from different doping level; frequently, doping levels are not stated in publications. Doping levels are often expressed in terms of room temperature resistivity and Figure 5-3 provides the correlation between electrical resistivity and impurity concentration at 300°K. The optical transmission of silicon is summarized in Figure 1-2.

DATA

All data presentations for silicon are listed in Table 5-1 and a summary of wavelength and temperature coverage is plotted in Figure 5-4. Most data for bulk silicon are believed to have been obtained from single crystal material, but experimenters have frequently failed to state the crystalline status of their specimens. Figures 5-5 to 5-14 and Tables 5-2 to 5-4 present refractive index data for bulk silicon for wavelengths from the visible region to 200 microns; Figure 5-15 shows the extinction coefficient for bulk silicon from 1.0 to 15 microns. The effect of the type of detector on the measured refractive index is evident from Figure 5-9. Figures 5-10 to 5-15 show data for doped specimens. Figures 5-14 and 5-15 present the optical properties of a highly doped

p-type surface on an n-type substrate, where the doped layer is considered to be semi-infinite; the effect of surface condition on the refractive index is also apparent from these Figures (see also Figures 5-23 and 5-29). Finally, Figure 5-16 shows the influence of wavelength on the refractive index of a silicon film. The effect of temperature on the refractive index is the subject of Figures 5-17 to 5-26 for temperatures between 77 and 960°K.

Intrinsic silicon shows good agreement in refractive index data and no large difference in refractive index is observable between bulk and films. No significant difference is detected between intrinsic bulk, single crystal and polycrystalline refractive indices. Doped materials do not exhibit a significant correlation between type and degree of doping, and refractive index.

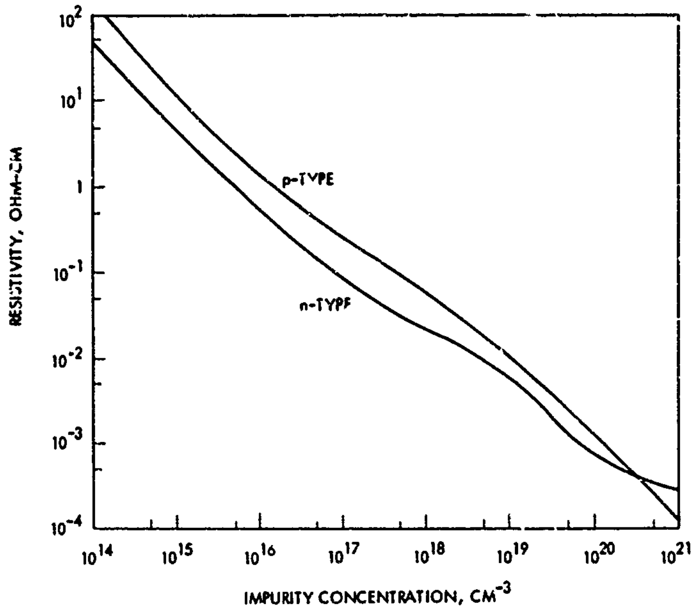

Figure 5-3. Resistivity at 300°K versus Impurity Concentration in Silicon [Irvin, (5250)]

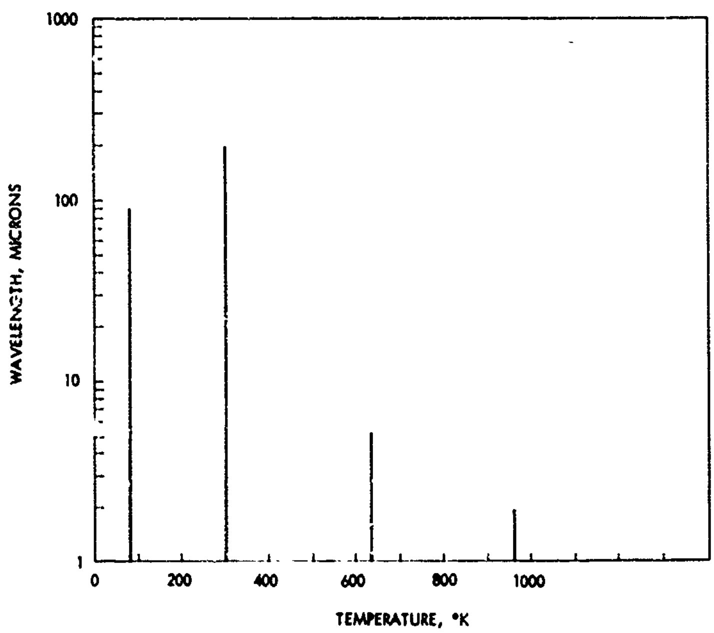

Figure 5-4. Wavelength and Temperature Range of Silicon Data

Table 5-1. List of Silicon Data

Figure	Table	n or k	Form	Crystal	Wavelength Range (microns) From	To	Remarks	Parameter
5-5	5-2	n	Bulk	*	1.4	11		Wavelength
5-6		n	Bulk	Single	0.1	5		Wavelength
	5-3	n	Bulk	Single	26	200		Wavelength
5-7		n	Bulk	Single	1.1	4.8		Wavelength
5-8		n	Bulk	*	0.1	5	100, 297°K	Wavelength
5-9		n	Bulk	*	0.03	12		Wavelength
	5-4	n	Bulk	*	1.0	2.6	85, 300°K	Wavelength
5-10		n	Bulk	*	25	180	n-type	Wavelength
5-11		n	Bulk	*	25	180	p-type	Wavelength
5-12		n	Bulk	Poly	4	12		Wavelength
5-13		n	Bulk	*	3.5	8.5	vac. treated	Wavelength
5-14		n	Bulk	*	1	15	p-type	Wavelength
5-15		k	Bulk	*	1	15	p-type	Wavelength
5-16		n	Film	Poly	0.55	2.2		Wavelength
5-17		dn/dT	Bulk	Single	1.3	1.6	p-type, 109-750°K	Temperature
5-18		Δn	Bulk	*	1.0	4.5		Temperature
5-19		$\Delta n/n$	Bulk, Film	Single, *	3.0	3.0	77-400°K	Temperature
5-20		n	Bulk	*	1.1	4.8	100-297	Temperature
5-21		n	Bulk	*	1.3	5.2	p-type, 109-750°K	Temperature
5-22		n	Bulk	*	0.9	2.0	p-type, 280-960°K	Temperature
5-23		n	Bulk	*	25	180	n-type, 85-300°K	Temperature
5-24		n	Bulk	*	0.1	5.0	100 - 297°K	Temperature
5-25		n	Bulk	*	0.9	2.0	n-type, 280-960°K	Temperature
5-26		dn/dT	Bulk	*	0.45	2.0	n-type, 280-960°K	Temperature
5-27		n	Bulk	*	0.1	5.0		Pressure
5-28		n	Bulk	*	1	15	p-type	Surface
5-29		k	Bulk	*	1	15	p-type	Surface

*Not stated.

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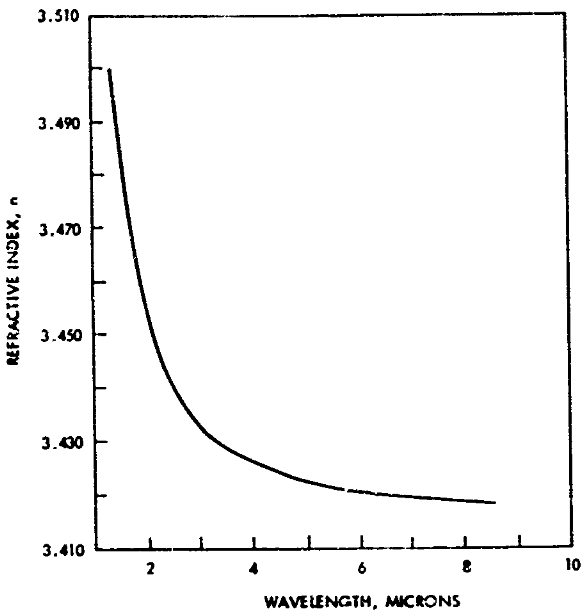
PARAMETER: Wavelength

MATERIAL: Silicon



FORM Bulk mm

THICKNESS NA (Prism)

RAY ORDINARY ☒, EXTRAORDINARY ☐

WAVELENGTH 1.4-11 μ

TEMPERATURE 299 °K

METHOD Deviation

REFERENCE Salzberg & Villa (3900)

REMARKS

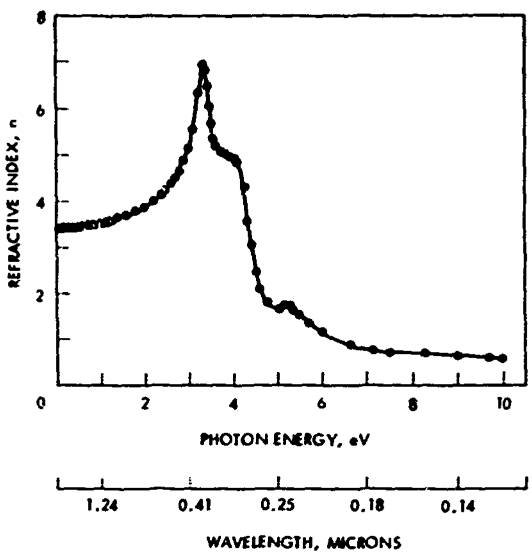
Figure 5-5

Wavelength, (Microns)	Refractive Index, n
1.3570	3.4975
1.3673	3.4962
1.3951	3.4929
1.5295	3.4795
1.6606	3.4696
1.7092	3.4664
1.8131	3.4608
1.9701	3.4537
2.1526	3.4476
2.3254	3.4430
2.4373	3.4408
2.7144	3.4358
3.00	3.4320
3.3033	3.4297
3.4188	3.4286
3.50	3.4284
4.00	3.4255
4.258	3.4242
4.50	3.4236
5.00	3.4223
5.50	3.4213
6.00	3.4202
6.50	3.4195
7.00	3.4189
7.50	3.4186
8.00	3.4184
8.50	3.4182
10.00	3.4179
10.50	3.4178
11.04	3.4176

Table 5-2

PARAMETER: Wavelength

MATERIAL: Silicon



FORM Bulk, Single Crystal

THICKNESS not stated mm

RAY ORDINARY ☒, EXTRAORDINARY ☐

WAVELENGTH 0.1 - 5 μ

TEMPERATURE 300 °K

METHOD Reflection

REFERENCE Philipp & Taft (5951)

REMARKS Values above 1.0 micron were taken from Salzberg & Villa (3900).

Figure 5-6

Wavelength (Microns)	Refractive Index, n
26 - 29	3.41 ± 0.03
111-200	3.41 ± 0.03

THICKNESS 0.5 - 2.0 mm

RAY ORDINARY ☒, EXTRAORDINARY ☐

WAVELENGTH 26-200 μ

TEMPERATURE 297 °K

METHOD Interference

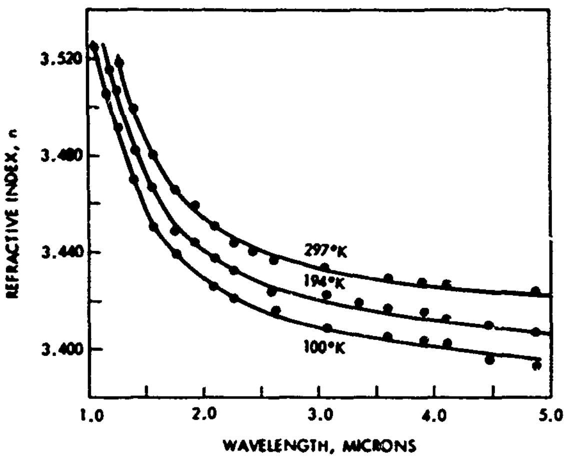
REFERENCE Aronson, et al. (16091)

REMARKS Crystal cut perpendicular to the [111] axis.

Table 5-3

PARAMETER: Wavelength

MATERIAL: Silicon



FORM Single Crystal Prism

THICKNESS NA mm

RAY ORDINARY ☒, EXTRAORDINARY ☐

WAVELENGTH 1.1-4.8 μ

TEMPERATURE 100-297 °K

METHOD Deviation

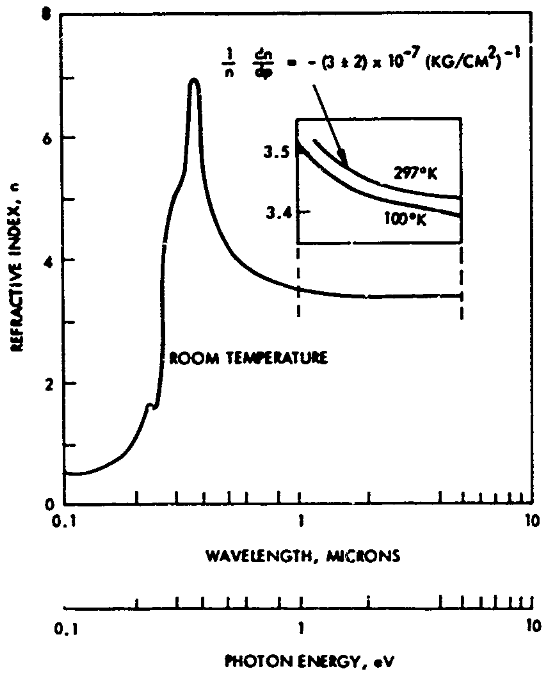
REFERENCE Cardona, et al. (620)

REMARKS

Figure 5-7

PARAMETER: Wavelength

MATERIAL: Silicon



FORM Bulk mm

THICKNESS not stated

RAY ORDINARY ☒, EXTRAORDINARY ☐

WAVELENGTH 0.1-5 μ

TEMPERATURE 100, 297 °K

METHOD not stated

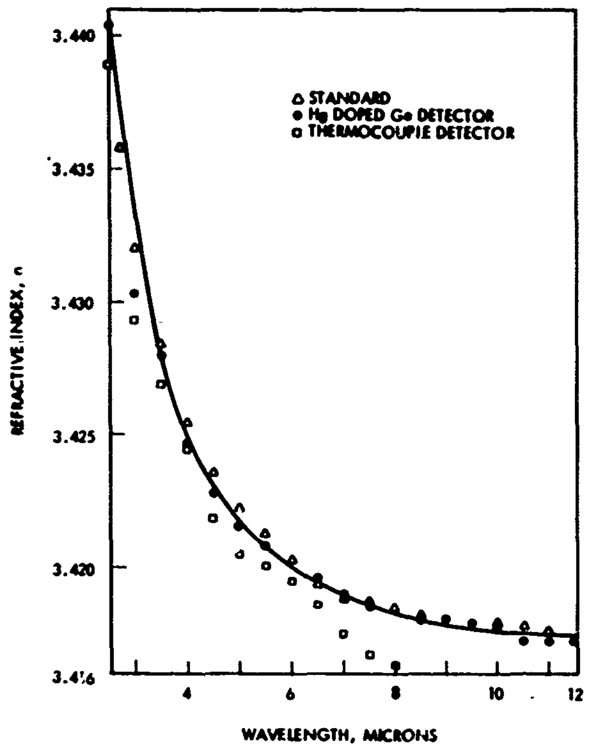
REFERENCE Evans (26567)

REMARKS

Figure 5-8

PARAMETER: Wavelength

MATERIAL: Silicon



FORM Bulk

THICKNESS NA (Prism) mm

RAY ORDINARY ☒, EXTRAORDINARY ☐

WAVELENGTH 0.03-12 μ

TEMPERATURE ~298 °K

METHOD Deviation

REFERENCE Hilton, et al., (25628)

REMARKS

Figure 5-9

Wavelength, (Microns)	Refractive Index, n
1.05	3.565
1.10	3.553
1.20	3.531
1.40	3.499
1.60	3.480
1.80	3.466
2.00	3.458
2.20	3.451
2.40	3.447
2.60	3.443

THICKNESS NA (Prism) mm

RAY ORDINARY ☒, EXTRAORDINARY ☐

WAVELENGTH 1.0-2.6 μ

TEMPERATURE ~298 °K

METHOD Deviation

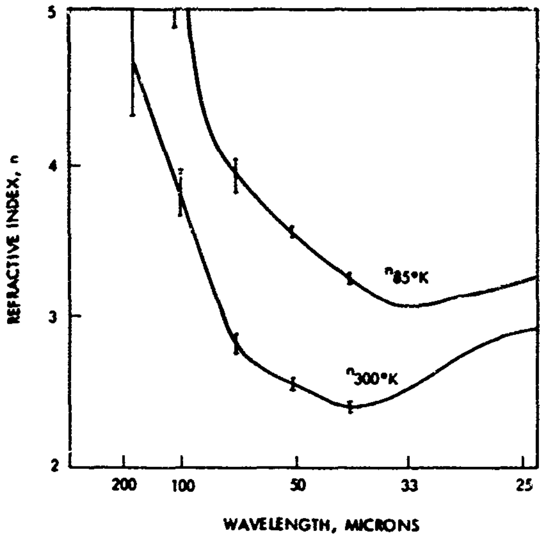
REFERENCE Briggs (13314)

REMARKS

Table 5-4

PARAMETER: Wavelength

MATERIAL: Silicon



FORM Bulk

THICKNESS 0.010 mm

RAY ORDINARY ☒, EXTRAORDINARY ☐

WAVELENGTH 25-180 μ

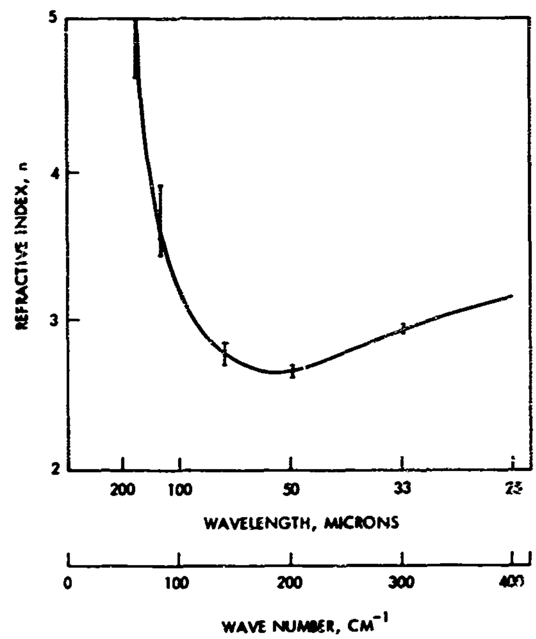
TEMPERATURE 85, 300 °K

METHOD Reflection

REFERENCE Balkanski & Besson (22653)

REMARKS Phosphorus-doped n-type silicon at concentration of 2.9×10^{17} cm^{-3} at 300°K.

Figure 5-10



THICKNESS 0.010 mm

RAY ORDINARY ☒, EXTRAORDINARY ☐

WAVELENGTH 25-180 μ

TEMPERATURE 300 °K

METHOD Reflection

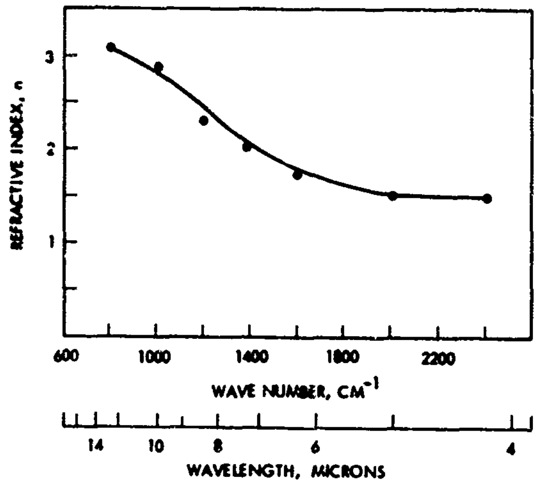
REFERENCE Balkanski & Besson (22653)

REMARKS Arsenic-doped p-type silicon with concentration of 1.7×10^{18} cm^{-3} at 300°K.

Figure 5-11

PARAMETER: Wavelength

MATERIAL: Silicon



FORM Bulk, polycrystalline

THICKNESS not stated mm

RAY ORDINARY ☒, EXTRAORDINARY ☐

WAVELENGTH 4-12 μ

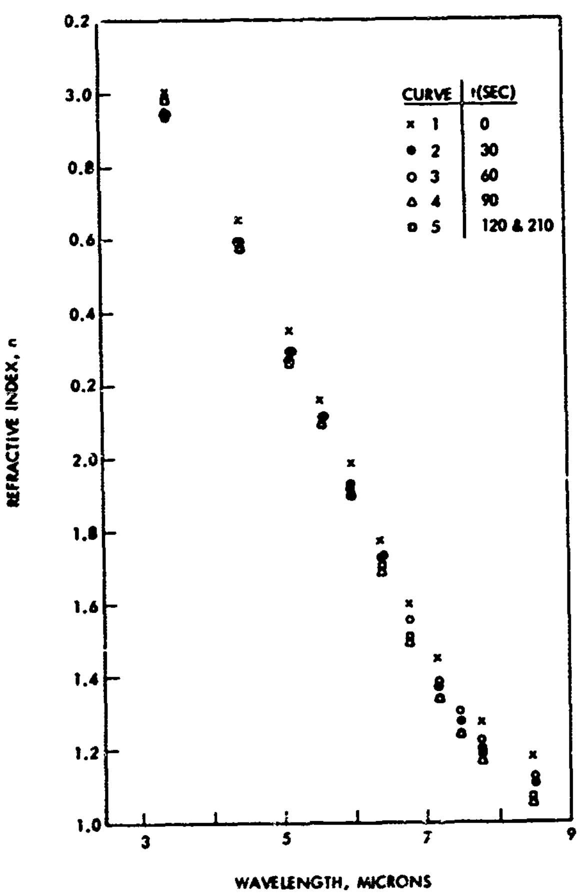
TEMPERATURE ~298 °K

METHOD Reflection

REFERENCE Simon (4799)

REMARKS Resistivity = 0.7 ohm-cm

Figure 5-12



THICKNESS not stated mm

RAY ORDINARY ☒, EXTRAORDINARY ☐

WAVELENGTH 3.5-8.5 μ

TEMPERATURE ~298 °K

METHOD Reflection

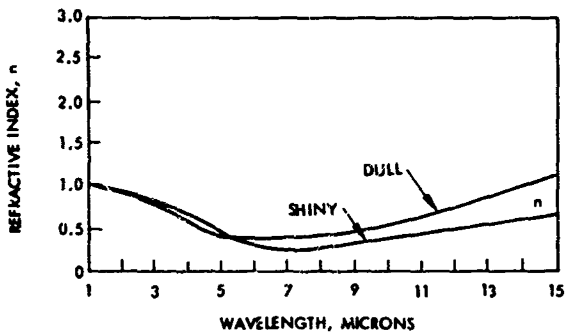
REFERENCE Spitzer, et al., (13860)

REMARKS Phosphorus-doped n-type silicon with concentration at 298°K of 7.5 x 10^{19} cm^{-3}. Material vacuum-heat treated at 1310°K.

Figure 5-13

PARAMETER: Wavelength

MATERIAL: Silicon



FORM p-type surface on n-type substrate

THICKNESS 1×10^{-2} (p-type) mm

RAY ORDINARY ☒ EXTRAORDINARY ☐

WAVELENGTH 1-15 μ

TEMPERATURE ~298 °K

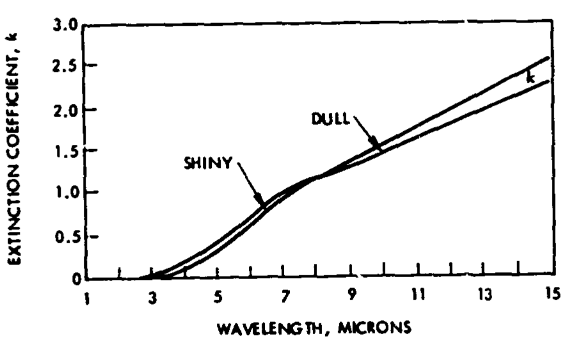
METHOD Reflection

REFERENCE Hall (13466)

REMARKS p-type surface produced by doping with boron.

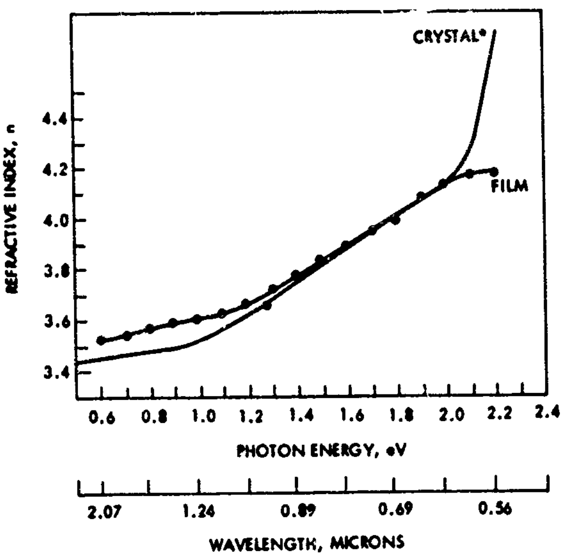
Figure 5-14

Figure 5-15



PARAMETER: Wavelength

MATERIAL: Silicon



* CRYSTAL DATA CALCULATED FROM REF (194)

FORM Film, amorphous

THICKNESS $(0.4\text{-}3.25) \times 10^{-4}$ mm

RAY ORDINARY ☒, EXTRAORDINARY ☐

WAVELENGTH 0.55-2.2 μ

TEMPERATURE 298 °K

METHOD

REFERENCE Grigorovici & Vancu (35455)

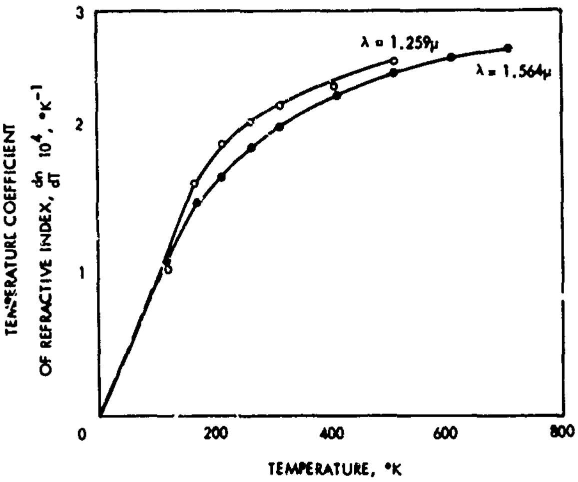
REMARKS Film produced by evaporation of pure silicon single crystal (resistivity = 10 ohm-cm) at $< 1 \times 10^{-5}$ torr using electron bombardment and lower end of silicon as crucible.

Note: crystal data refer to single crystals.

Figure 5-16

PARAMETER: Temperature

MATERIAL: Silicon



FORM Single Crystal

THICKNESS NA (Prism) mm

RAY ORDINARY ☒ , EXTRAORDINARY ☐

WAVELENGTH 1.26-1.56 μ

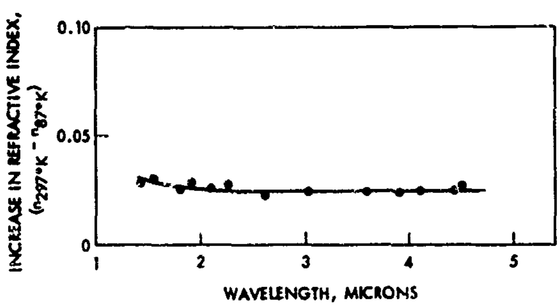
TEMPERATURE 109-750 °K

METHOD Deviation

REFERENCE Lukes (3382)

REMARKS p-type silicon, resistivity = 380 ohm-cm.

Figure 5-17



THICKNESS NA (Prism) mm

RAY ORDINARY ☒ , EXTRAORDINARY ☐

WAVELENGTH 1.0-4.5 μ

TEMPERATURE 87, 297 °K

METHOD Deviation

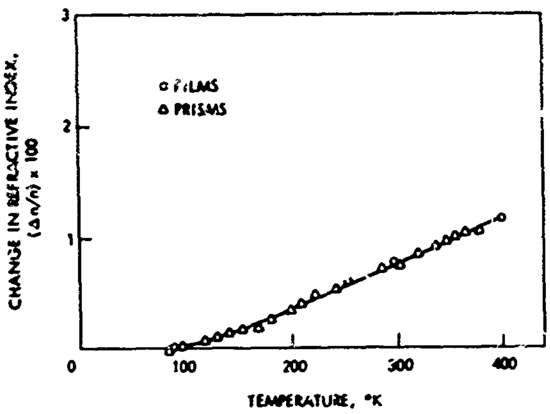
REFERENCE Cardona (2569)

REMARKS

Figure 5-18

PARAMETER: Temperature

MATERIAL: Silicon



FORM Single Crystal Film & Prism

THICKNESS Film 0.003-01010 mm

RAY ORDINARY ☒, EXTRAORDINARY ☐

WAVELENGTH 3.0 μ

TEMPERATURE 77-400 °K

METHOD Interference for films, deviation for prism.

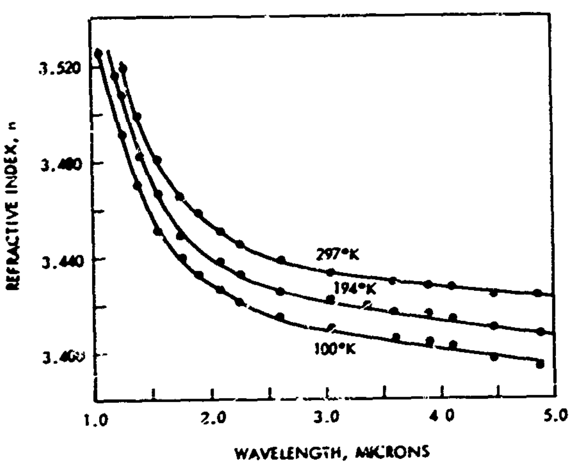
REFERENCE Cardona, et al. (620)

REMARKS

Equation:

$$(1/n)(dn/dT) = (3.9 \pm 0.4) \times 10^{-5}\ (°K)^{-1}$$

Figure 5-19



THICKNESS NA (Prism) mm

RAY ORDINARY ☒, EXTRAORDINARY ☐

WAVELENGTH 1.1-4.8 μ

TEMPERATURE 100-297 °K

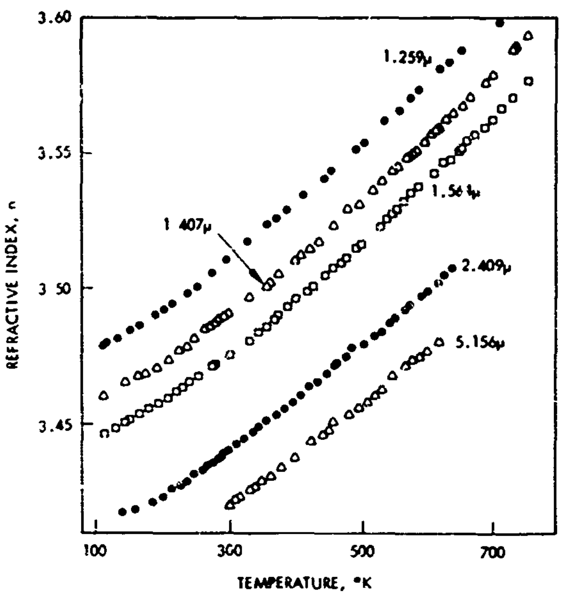
METHOD Deviation

REFERENCE Cardona, et al. (620)

REMARKS

Figure 5-20

PARAMETER: Temperature **MATERIAL:** Silicon



FORM Bulk

THICKNESS NA (Prism) mm

RAY ORDINARY ☒ , EXTRAORDINARY ☐

WAVELENGTH 1.3-5.2 μ

TEMPERATURE 109-750 °K

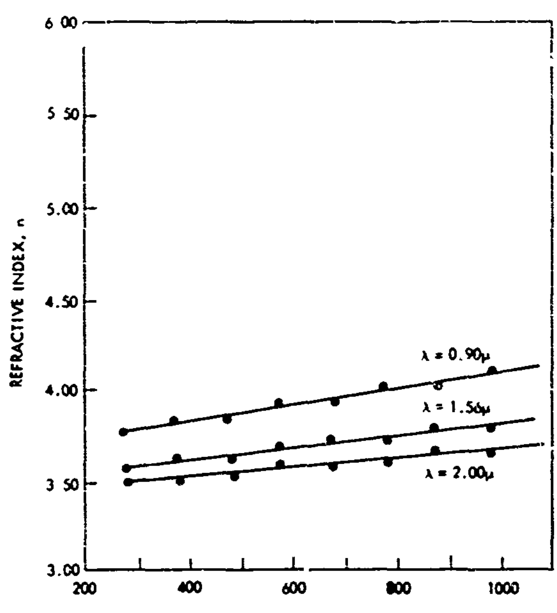
METHOD Deviation

REFERENCE Lukes (4541)

REMARKS p-type silicon,

Resistivity = 380 ohm-cm.

Figure 5-21



THICKNESS 1.77 (Bulk) mm

RAY ORDINARY ☒ , EXTRAORDINARY ☐

WAVELENGTH 0.9-2.0 μ

TEMPERATURE 280-960 °K

METHOD Emissivity

REFERENCE Sato (29333)

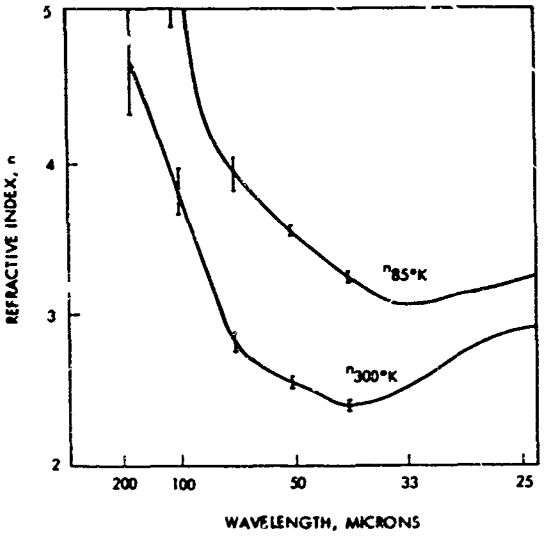
REMARKS n-type silicon, p-doped,

resistivity = 15 ohm-cm.

Figure 5-22

PARAMETER: Temperature

MATERIAL: Silicon



FORM Bulk

THICKNESS 0.010 mm

RAY ORDINARY ☒, EXTRAORDINARY ☐

WAVELENGTH 25-180 μ

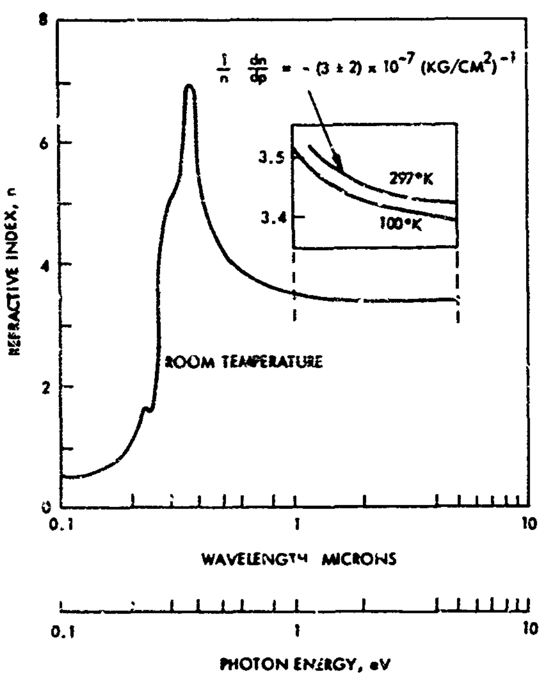
TEMPERATURE 85, 300 °K

METHOD Reflection

REFERENCE Balkanski and Besson (22653)

REMARKS Phosphorus-doped n-type silicon at concentration of 2.9×10^{17} cm^{-3} at 300°K.

Figure 5-23



THICKNESS not stated mm

RAY ORDINARY ☒, EXTRAORDINARY ☐

WAVELENGTH 0.1-5 μ

TEMPERATURE 100, 297 °K

METHOD not stated

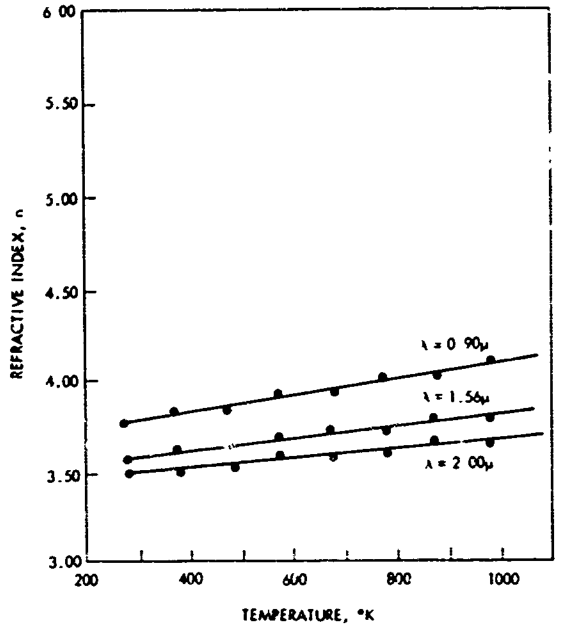
REFERENCE Evans (26567)

REMARKS

Figure 5-24

PARAMETER: Temperature

MATERIAL: Silicon



FORM Bulk

THICKNESS 1.77 mm

RAY ORDINARY ☒, EXTRAORDINARY ☐

WAVELENGTH 0.9 - 2.0 μ

TEMPERATURE 280 - 960 °K

METHOD Emissivity*

REFERENCE Sato (29333)

REMARKS n-type silicon, phosphorus-doped, resistivity = 15 Ω -cm.

Figure 5-25

*Calculated from:

$$\text{Emissivity} = \frac{4n}{(n+1)^2}$$

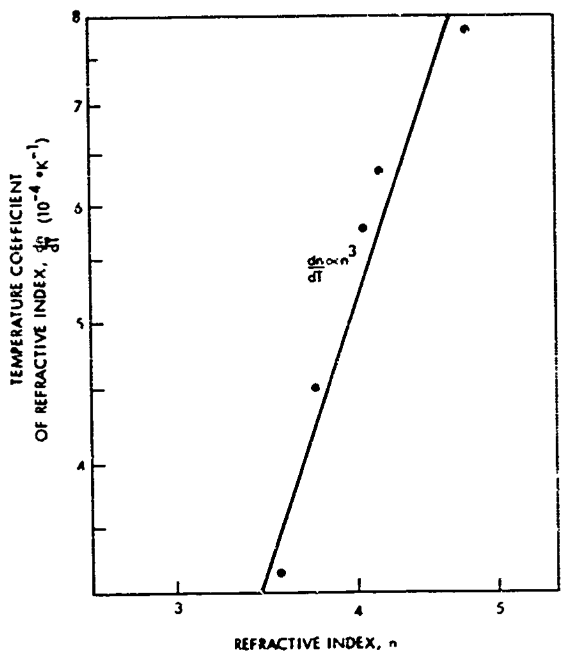
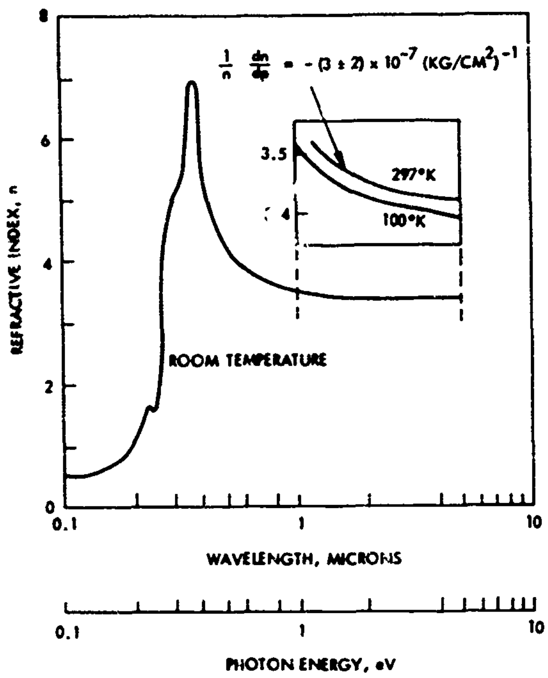


Figure 5-26

PARAMETER: Pressure

MATERIAL: Silicon



FORM Bulk

THICKNESS not stated mm

RAY ORDINARY ☒, EXTRAORDINARY ☐

WAVELENGTH 0.1-5.0 μ

TEMPERATURE 297 °K

METHOD not stated

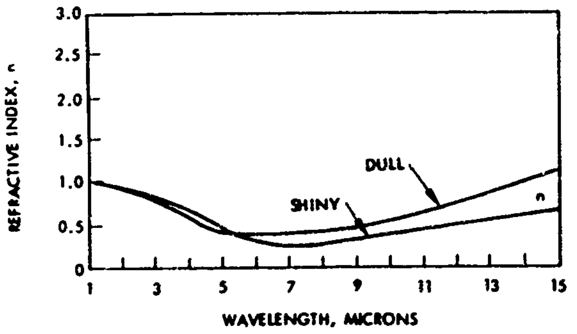
REFERENCE Evans (26567)

REMARKS

Figure 5-27

PARAMETER: Surface Condition

MATERIAL: Silicon



FORM p-type surface on n-type substrate

THICKNESS 1×10^{-2} (p-type) film: mm

RAY ORDINARY ☑ EXTRAORDINARY ☐

WAVELENGTH 1-15 μ

TEMPERATURE ~298 °K

METHOD Reflection

REFERENCE Hall

REMARKS p-type surface produced by doping with boron.

Figure 5-28

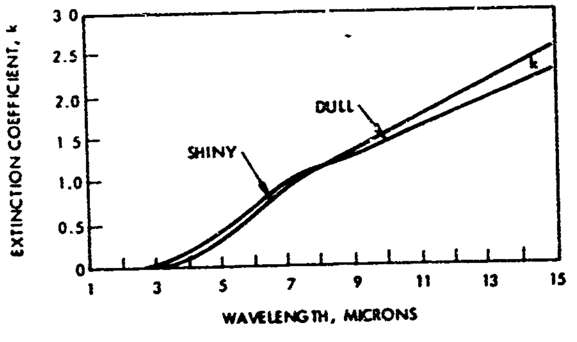


Figure 5-29

GERMANIUM

INTRODUCTION

Germanium is a semiconductor that has found application in infrared optics, transistors, diodes, rectifiers, thermoelectric devices and in brazing alloys. Recovery of germanium from ores involves a series of steps including pyro and hydrometallurgy to produce a germanium concentrate, chlorination to obtain a purer germanium tetrachloride, hydrolysis to produce still purer germanium dioxide and reduction of the oxide to the metal with zinc. This "first reduction metal" is zone refined to produce semiconductor grade germanium, and an increase in resistivity is accomplished from a minimum of 5 ohm-cm. for first reduction metal to a minimum of 40 ohm-cm. for the zone-refined metal. The resistivity of intrinsic germanium is 47 ohm-cm.

The physical properties of intrisic germanium are summarized in Table 1-1, and its optical transmission spectrum is plotted in Figure 1-3. Impurities in germanium have an effect on several properties including electrical resistivity and optical transmission. Indeed, even films prepared by evaporation of highly purified intrinsic germanium have shown to be p-type germanium with a resistivity of 3 to 10 ohm-cm, [Ref: Courvoisier, [1963]]. It is therefore apparent that a comparison of optical properties of evaporated films, measured by various workers, may be unrealistic because of different doping levels.

Doping levels are often expressed in terms of room temperature resistivity and Figure 5-30 permits the conversion between electrical resistivity and impurity concentration, at 300°K.

DATA

All data presentations for germanium are listed in Table 5-5 and a summary of wavelength and temperature coverage is plotted in Figure 5-31.

Figure 5-32 presents a comparison in refractive indices of bulk and film germanium and also provides an introductory presentation of

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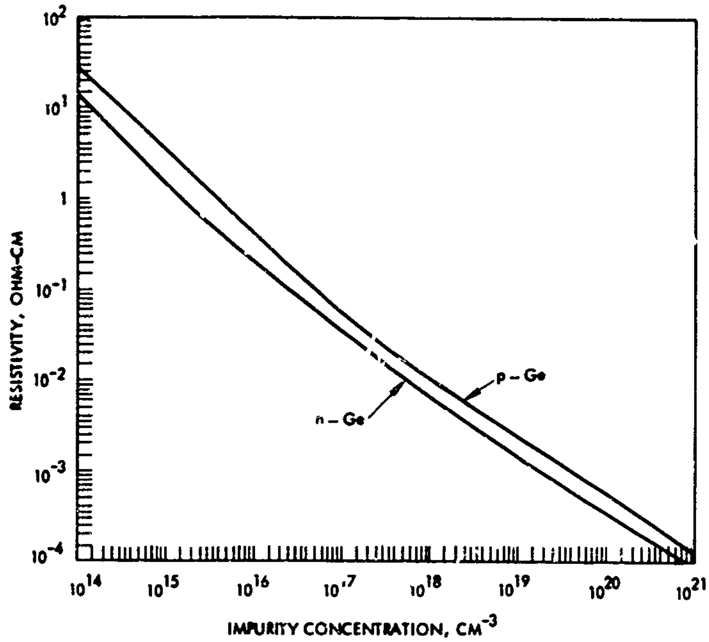


Figure 5-30. Resistivity versus Impurity Concentration for Ge, 300°K

Ref: Sze and Irvin (34530)

the effect of the nature of the evaporation atmosphere during film deposition. Data in Figure 5-32 as well as subsequent Figures show a consistently higher refractive index for films as compared to bulk germanium. Some observers [Ref: Wales, et al. (31497)] believe that this difference is caused by the presence of at least one additional loosely bonded electron than normal at the surface of the crystallites. Germanium films, deposited onto substrates that are below 673°K, are amorphous and will assume the refractive index of bulk material after annealing; annealing of such films caused crystallite formation. Similarly, deposition onto heated substrates (>673°K) resulted in the formation of films having bulk refractive index. Figures 5-33 to 5-48 and Tables 5-6 to 5-10 present additional spectral data for the refractive index of bulk and film germanium. As was the case with silicon, no generalization is possible for the effect of doping on the refractive

Table 5-5. List of Germanium Data

Figure	Table	n or k	Form	Crystal	Wavelength Range (microns) From	To	Remarks	Parameter
5-32		n	Bulk, Film	*	1.0	6.0	Data comparison	Wavelength
5-33		n	Bulk	Single	0.6	1.7	300°K	Wavelength
5-34		n	Bulk	Single	0.6	1.7	120°K	Wavelength
5-35		n	Bulk	Single	2	16		Wavelength
5-36		n	Bulk	*	1.5	13		Wavelength
5-37		n	Bulk	Single	0.6	5.5	87-297°K	Wavelength
5-38		n	Bulk	*	0.8	5.5	Several doping levels	Wavelength
5-39		n	Bulk	Single	0.1	1.8		Wavelength
	5-6	n	Bulk	Single	25	143	7.5, 297°K	Wavelength
5-40		n	Bulk	Single	0.8	15		Wavelength
	5-7	n	Bulk	Single	2.0	2.4		Wavelength
5-41		n	Bulk		70	500		Wavelength
	5-8	n	Bulk	Single, polycryst	2	16		Wavelength
	5-9	n	Bulk		1.8	2.6		Wavelength
5-42		n	Bulk	*	4	14		Wavelength
5-43		n	Bulk	*	5	35	n-doped, p-doped	Wavelength
5-44		k	Bulk	*	12	35	n-doped	Wavelength
	5-10	n	Film	*	8.7	12.4	77, 300°K	Wavelength
5-45		n	Film		1.0	5.0		Wavelength
5-46		n	Film	*	0.6	10		Wavelength
5-47		n	Film	Polycryst	0.7	3.1	p-doped	Wavelength
5-48		n	Film	*	0.85	2.5		Wavelength
5-49		n	Bulk	Single	1.8	5.5	n-doped	Temperature
5-50		n	Bulk	*	2.0	2.5	n-doped	Temperature
5-51		dn/dT	Bulk		2.0	2.5	n doped	Temperature
5-52		n^2	Bulk	Single	1.5	2.2	80-460°K	Temperature
	5-11	n	Bulk	*	23	143	7.5, 297°K	Temperature

*Not stated.

Table 5-5 (continued)

Figure	Table	n or k	Form	Crystal	Wavelength Range (microns) From	To	Remarks	Parameter
5-53		n	Bulk	Single	0.6	1.7	300°K	Temperature
5-54		n	Bulk	Single	0.6	1.7	120°K	Temperature
5-55		n	Bulk	*	1.8	5.3	87-297°K	Temperature
5-56		$\Delta n/n$	Bulk, Film	*	3.0	3.0	90-400°K	Temperature
	5-12	dn/dT	*	*	2.25	2.25		Temperature
	5-13	n	Bulk	Single	2.0	2.4		Temperature
	5-14	n	Film	*	8.7	12.4	77-300°K	Temperature
5-57		$\Delta n/n$	Film	*	2.0	4.0	77-395°K	Temperature
	5-15	(1/n)dn/dp	Film	*	3.0	3.0		Pressure
	5-16	(1/n)dn/dp	Film	*	3	3	From RF dielectric data	Pressure
	5-17	(1/n)dn/dp	Film	*	2.0	4.0		Pressure
	5-18	n	Film	*	2.64	2.64	0.07-6.5μ Thickness	Film Thickness
5-58		n	Film	*	2.2	2.2	Ge/ZnS Film	Film Composition
5-59		n	Film	*	1.0	5.0		Film Deposition Rate
5-60		n	Film	*	1.0	5.0	Air atmosphere	Atmosphere Film Deposition
5-61		n	Film	*	0.5	5.0	Vacuum atmosphere	Atmosphere Film Deposition
5-62		n	Film	*	1.0	5.0	Oxygen atmosphere	Atmosphere Film Deposition
5-63		n	Film	*	1.0	5.0	Nitrogen atmosphere	Atmosphere Film Deposition
5-64		n	Film	*	1.0	5.0	Nitrogen atmosphere	Atmosphere Film Deposition
5-65		n	Film	*	1.0	5.0	Hydrogen atmosphere	Atmosphere Film Deposition
5-66		n	Film	*	1.0	5.0	273°K	Deposition Substrate Temperature
5-67		n	Film	*	1.0	5.0	373-473°K	Deposition Substrate Temperature
5-68		n	Film	*	1.0	5.0	673°K	Deposition Substrate Temperature
5-69		n	Film		1.0	5.0	773-873°K	Deposition Substrate Temperature
5-70		n	Film	Amorphous and polycryst.	1.25	6.5	293-573°K	Deposition Substrate Temperature
5-71		Δn	Bulk	*	1.6	2.2		Electric Field

*Not stated.

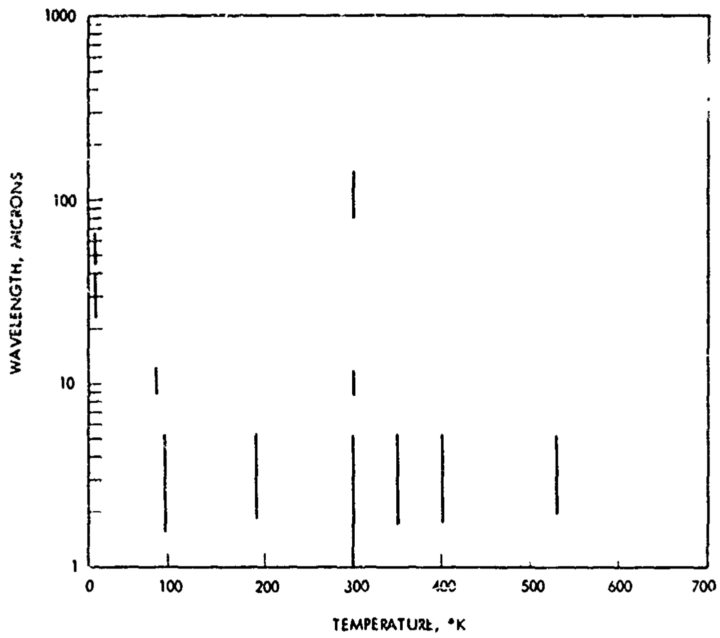


Figure 5-31. Wavelength and Temperature Range of Germanium Data

index. The effect of temperature on the refractive index is covered in Figures 5-49 to 5-57 and Tables 5-11 to 5-14. Tables 5-15 to 5-17 provide information on the effect of pressure on the refractive index. The effect of film thickness on the refractive index at 2.64 microns is indicated in Table 5-18 and a decreasing refractive index with increasing film thickness is observed. It is possible to make films with a continuously variable refractive index, as shown in Figure 5-58. These films are made by the simultaneous evaporation of germanium and zinc sulfide from two sources and may find application as absorption cut-off filters with variable cut-off frequency.

The refractive index of germanium is not greatly affected by the deposition rate, as shown in Figure 5-59. The effect of the nature of the deposition atmosphere is the subject of Figures 5-60 to 5-65 where the atmosphere consisted of air, vacuum, oxygen, nitrogen and hydrogen, respectively, with the gases at a pressure of approximately 1 x 10^{-4} Torr. Except for a slight lowering in refractive index after

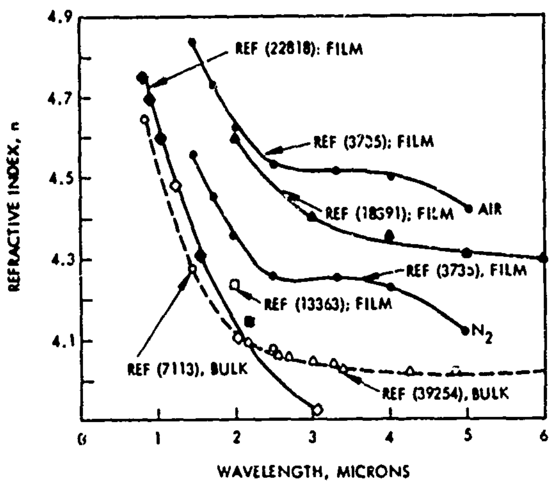
deposition in oxygen, no significant effect was observed. The low index from deposition in an oxygen environment may be caused by the formation of germanium dioxide, having a refractive index of approximately two in the near-infrared.

The substrate temperature during deposition has an effect on the crystallinity of the film. According to Davey [1961], germanium films which are deposited at a substrate temperature below 448°K, are amorphous. Data by Wales, et al. (31497) indicate a lower refractive index for films, deposited on hot substrates, (Figure 5-66 to 5-69). This is in contrast to the results of Gisin and Ivanov (41222), Figure 5-70, who obtained a higher refractive index for substrates at 523 - 573°K than at 403 - 423°K, their refractive indices for 403-423°K and 293 - 303°K were nearly identical, indicative of an amorphous state at both lower temperature ranges.

The dependence of the refractive index on the electric field is illustrated in Figure 5-71 in a study of the Franz-Keldysh Effect.

PARAMETER: Wavelength

MATERIAL. Germanium



FORM Bulk and Film

THICKNESS Various, not stated mm

RAY ORDINARY ☒, EXTRAORDINARY ☐

WAVELENGTH 1 - 6 μ

TEMPERATURE ~298 °K

METHOD Various

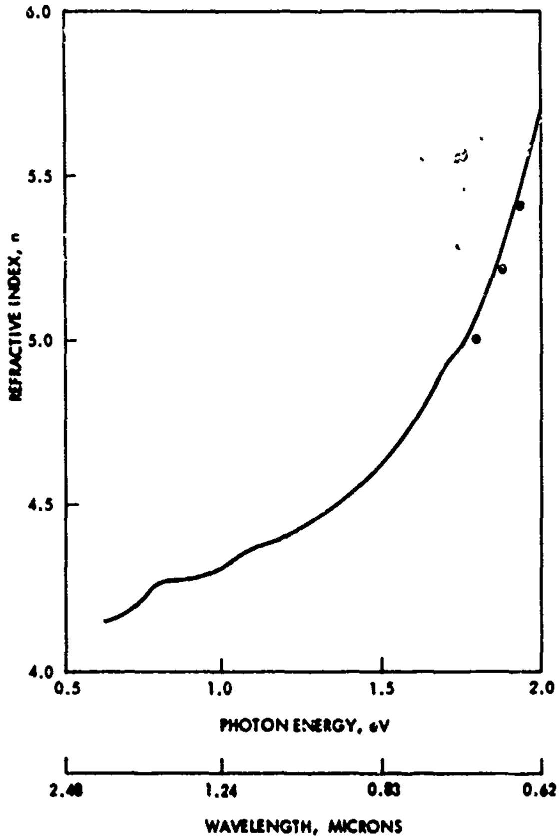
REFERENCE Wales, et al. (31497)

REMARKS

Figure 5-32

PARAMETER: Wavelength

MATERIAL: Germanium



FORM Bulk, Single Crystal

THICKNESS Not stated mm

RAY ORDINARY ☒, EXTRAORDINARY ☐

WAVELENGTH 0.6 - 1.7 μ

TEMPERATURE 120, 300 °K

METHOD Reflection

REFERENCE Potter (27255)

REMARKS

Figure 5-33
(300°K)

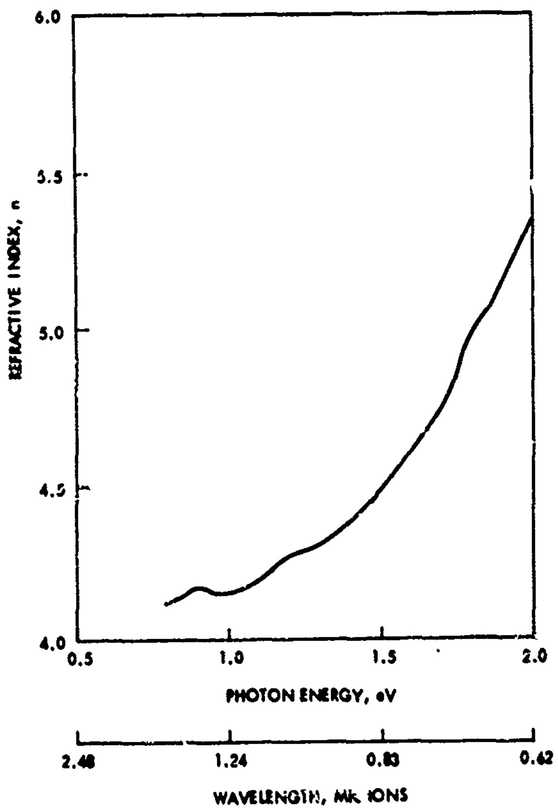
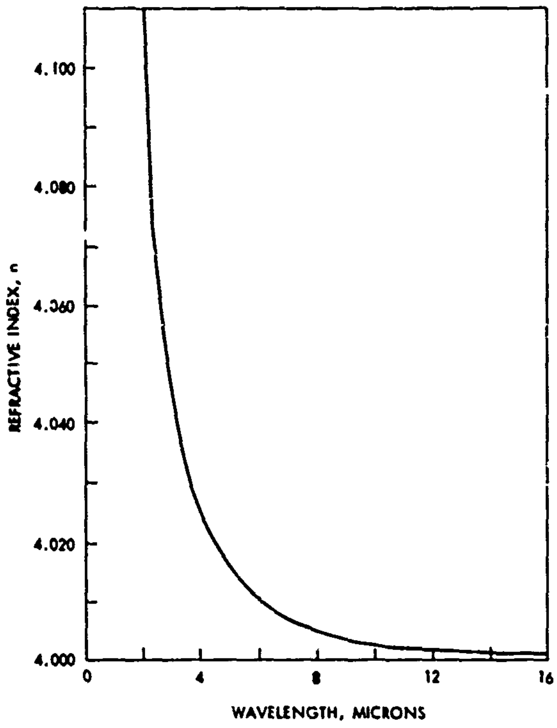


Figure 5-34
(120°K)

PARAMETER: Wavelength

MATERIAL: Germanium



FORM Bulk, Single Crystal

THICKNESS NA (Prism) mm

RAY ORDINARY ☒ , EXTRAORDINARY ☐

WAVELENGTH 2 - 16 μ

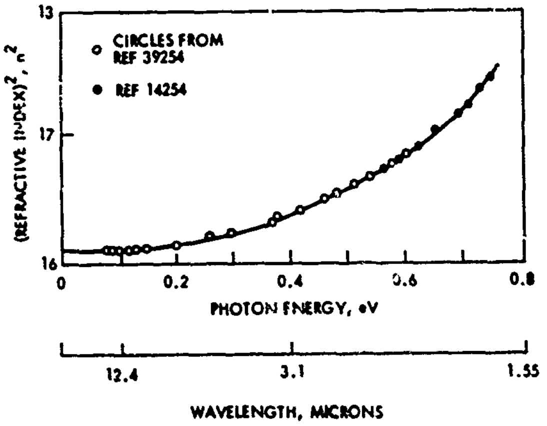
TEMPERATURE 300 °K

METHOD Deviation

REFERENCE Salzberg and Villa (3900)

REMARKS

Figure 3-35



THICKNESS NA (Prism) mm

RAY ORDINARY ☒ , EXTRAORDINARY ☐

WAVELENGTH 1.5 - 13 μ

TEMPERATURE 291 °K

METHOD Deviation

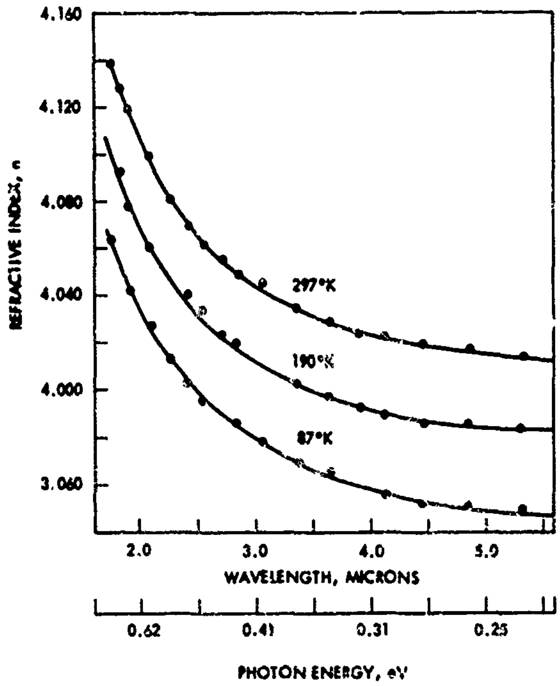
REFERENCE Kornfeid (14254)

REMARKS Resistivity = 50 ohm-cm

Figure 5-36

PARAMETER: Wavelength

MATERIAL: Germanium



FORM Bulk. Single Crystal

THICKNESS NA (Prism) mm

RAY ORDINARY ☒, EXTRAORDINARY ☐

WAVELENGTH 0.6 - 5.5 μ

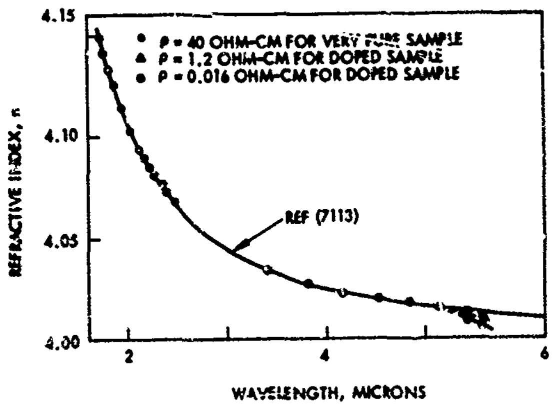
TEMPERATURE 87 - 297 °K

METHOD Deviation

REFERENCE Cardona, et al. (620)

REMARKS

Figure 5-37



THICKNESS NA (Prism) mm

RAY ORDINARY ☒, EXTRAORDINARY ☐

WAVELENGTH 0.8 - 5.5 μ

TEMPERATURE 300 °K

METHOD Deviation

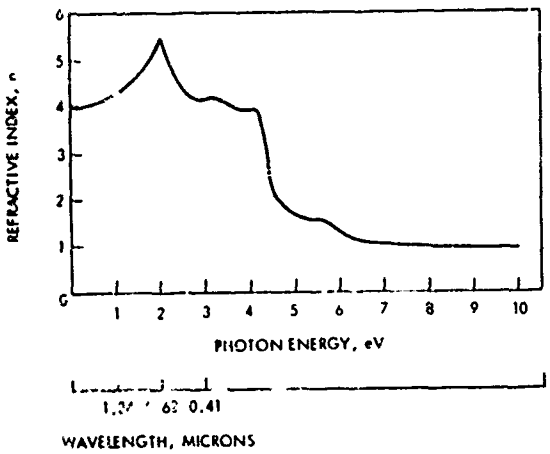
REFERENCE Lukes (3915)

REMARKS Pure and n-type germanium, resistivity shown on graph.

Figure 5-38

PARAMETER: Wavelength

MATERIAL: Germanium



FORM Bulk, Single Crystal

THICKNESS Not stated mm

RAY ORDINARY ☒ , EXTRAORDINARY ☐

WAVELENGTH 0.1 - 1.8 μ

TEMPERATURE 300 °K

METHOD Reflection

REFERENCE Philipp and Taft (7113)

REMARKS Data above 1.77 Microns taken from Salzberg and Villa (3900).

Figure 5-39

Wavelength, (Microns)	Temperature °K	Refractive Index, n
23-40	7.5	3.98 ±0.02
45-67	7.5	3.90 ±0.02
83-143	297	3.98 ±0.02

THICKNESS 0.5 - 2.0 mm

RAY ORDINARY ☒ , EXTRAORDINARY ☐

WAVELENGTH 23 - 143 μ

TEMPERATURE 7.5, 297 °K

METHOD Interference

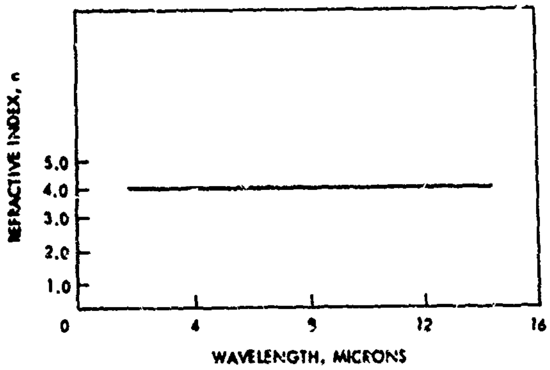
REFERENCE Aronson, et al. (16091)

REMARKS Crystal cut perpendicular to the [111] axis.

Table 5-6

PARAMETER: Wavelength

MATERIAL: Germanium



FORM Bulk, Single Crystal

THICKNESS ~7 mm

RAY ORDINARY ☒, EXTRAORDINARY ☐

WAVELENGTH 0.8 - 15.2 μ

TEMPERATURE ~297 °K

METHOD Transmission, Reflection

REFERENCE Oswald and Schade (2139)

REMARKS Resistivity = 56 ohm-cm.

Figure 5-40

Wavelength, (Microns)	Refractive Index, n
2.00	4.1254
2.10	4.1145
2.30	4.0980
2.40	4.0918

THICKNESS 3.06 mm

RAY ORDINARY ☒, EXTRAORDINARY ☐

WAVELENGTH 2.0 - 2.4 μ

TEMPERATURE 297.5 °K

METHOD Interference

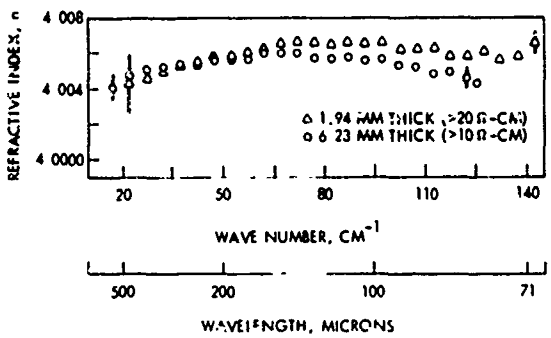
REFERENCE Rank, et al. (39713)

REMARKS Measurements in vacuo.

Table 5-7

PARAMETER: Wavelength

MATERIAL: Germanium



FORM Bulk

THICKNESS 1.89, 6.23 mm

RAY ORDINARY ☒ , EXTRAORDINARY ☐

WAVELENGTH 70 - 500 μ

TEMPERATURE ~300 °K

METHOD Interference

REFERENCE Randall and Rawcliffe (33251)

REMARKS Resistivity:

1.94 mm. sample, 20 ohm-cm.

6.23 mm. sample, 10 ohm-cm.

Figure 5-41

PARAMETER: Wavelength

MATERIAL: Germanium

Wavelength (Microns)	Index		
	Single-crystal		Polycrystal
	n_1*	n	n
2.0581	4.1016	4.1016	4.1018
2.1526	4.0917	4.0919	4.0919
2.3126	4.0788	4.0786	4.0785
2.4374	4.0706	4.0708	4.0709
2.577	4.0610	4.0609	4.0608
2.7144	4.0554	4.0552	4.0554
2.998	4.0453	4.0452	4.0452
3.3033	4.0370	4.0369	4.0372
3.4188	4.0336	4.0334	4.0339
4.258	4.0217	4.0216	4.0217
4.866	4.0170	4.0170	4.0167
6.2[illegible]6	4.0092	4.0094	4.0095
8.66	4.0036	[illegible].0043	4.0043
9.72	4.0026	4.0034	4.0033
11.04	4.0020	4.0026	4.0025
12.20	4.0018	4.0023	4.0020
13.02	4.0016	4.0021	4.0018
14.21	4.0015		
15.08	4.0014		
16.00	4.0012		

*n_1 previously published data from Salzberg and Villa (3900)

FORM Bulk

THICKNESS NA (Prism) mm

RAY ORDINARY ☒, EXTRAORDINARY ☐

WAVELENGTH 2 - 16 μ

TEMPERATURE 300 °K

METHOD Deviation

REFERENCE Salzberg and Villa (39254)

REMARKS Single and polycrystalline material

Table 5-8

Wavelength (Microns)	Refractive Index, n
1.80	4.143
1.85	4.135
1.90	4.129
2.00	4.116
2.10	4.104
2.20	4.092
2.30	4.085
2.40	4.078
2.50	4.072
2.60	4.068

THICKNESS NA (Prism) mm

RAY ORDINARY ☒, EXTRAORDINARY ☐

WAVELENGTH 1.8 - 2.6 μ

TEMPERATURE ~298 °K

METHOD Deviation

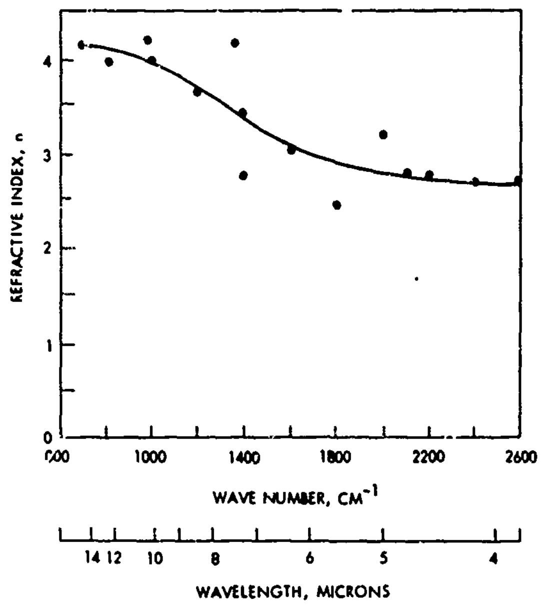
REFERENCE Briggs (13314)

REMARKS

Table 5-9

PARAMETER: Wavelength

MATERIAL: Germanium



FORM Bulk

THICKNESS ~0.8 mm

RAY ORDINARY ☒, EXTRAORDINARY ☐

WAVELENGTH 4 - 14 μ

TEMPERATURE Not stated °K

METHOD Reflection

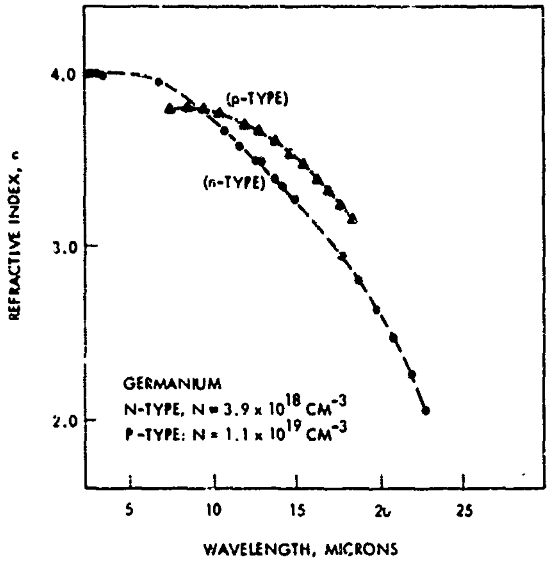
REFERENCE Simon (4799)

REMARKS n-type material with resistivity 1 ohm-cm at 297° K

Figure 5-42

PARAMETER: Wavelength

MATERIAL: Germanium



FORM Bulk

THICKNESS $\sim 10^{-2}$ mm

RAY ORDINARY ☒ , EXTRAORDINARY ☐

WAVELENGTH 5 - 35 μ

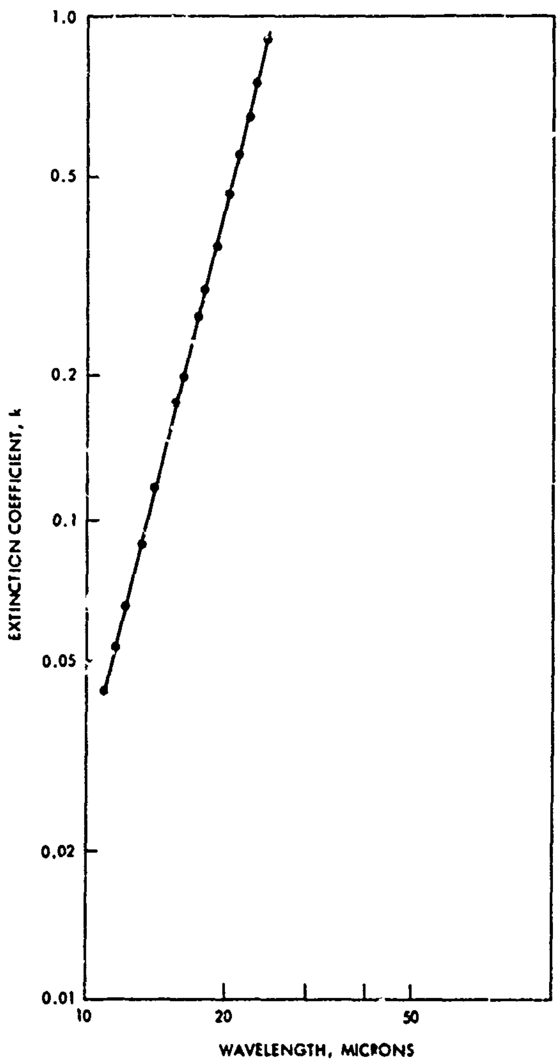
TEMPERATURE 297 °K

METHOD Transmission, Reflection

REFERENCE Spitzer and Fan (791)

REMARKS n-type, arsenic-doped material, concentration = 3.9×10^{18} cm^3. p-type, gallium-doped, concentration = 1.1×10^{19} cm^{-3}.

Figure 5-43



THICKNESS $\sim 10^{-2}$ mm

RAY ORDINARY ☒ , EXTRAORDINARY ☐

WAVELENGTH 12 - 35 μ

TEMPERATURE 297 °K

METHOD Transmission, Reflection

REFERENCE Spitzer and Fan (791)

REMARKS n-type, arsenic doped material, concentration = 3.9×10^{18} cm^{-3}

Figure 5-44

PARAMETER: Wavelength

MATERIAL: Germanium

Wavelength, (Microns)	Refractive Index, n	
	77°K	300°K
8.66	3.77	3.92
9.4	3.81	3.90
10.2	3.81	3.93
11.22	3.81	3.92
12.35	3.82	3.93

FORM Film

THICKNESS 0.227 mm

RAY ORDINARY ☒, EXTRAORDINARY ☐

WAVELENGTH 8.66 - 12.35 μ

TEMPERATURE 77, 300 °K

METHOD Interference

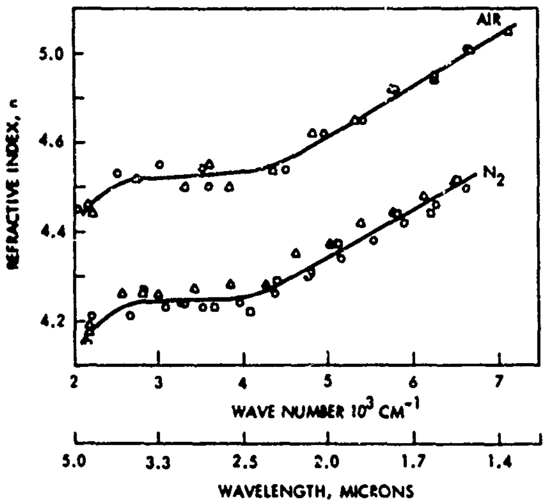
REFERENCE Collins (40273)

REMARKS

Table 5-10

PARAMETER: Wavelength

MATERIAL: Germanium



Air plots: O, layer with d = 1·092 μ; Δ, d = 1·010 μ.

Nitrogen plots: O, layer with d = 1·340 μ; Δ, d = 1·364 μ · □d = 1·449 μ. x determined from Brewster angle; remaining plots from geometric thickness of film.

FORM Film

THICKNESS (see remarks), ~10^{-3} mm

RAY ORDINARY ☒, EXTRAORDINARY ☐

WAVELENGTH 1 - 5 μ

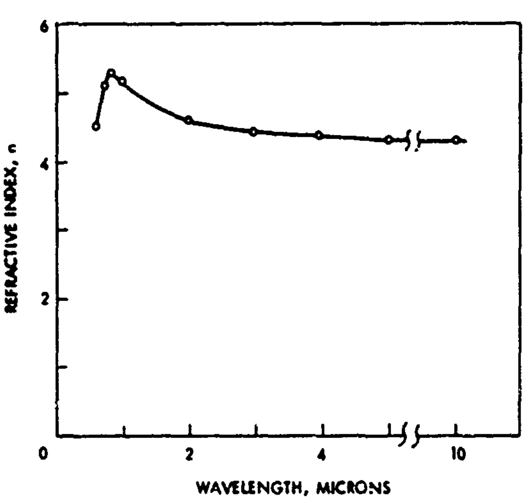
TEMPERATURE ~297 °K

METHOD Interference, Reflection

REFERENCE Huldt and Staflin (3735)

REMARKS Glass substrate;

Figure 5-45



THICKNESS 4 x 10^{-5} - 1 x 10^{-3} mm

RAY ORDINARY ☒, EXTRAORDINARY ☐

WAVELENGTH 0.6 - 10 μ

TEMPERATURE 297 °K

METHOD Interference

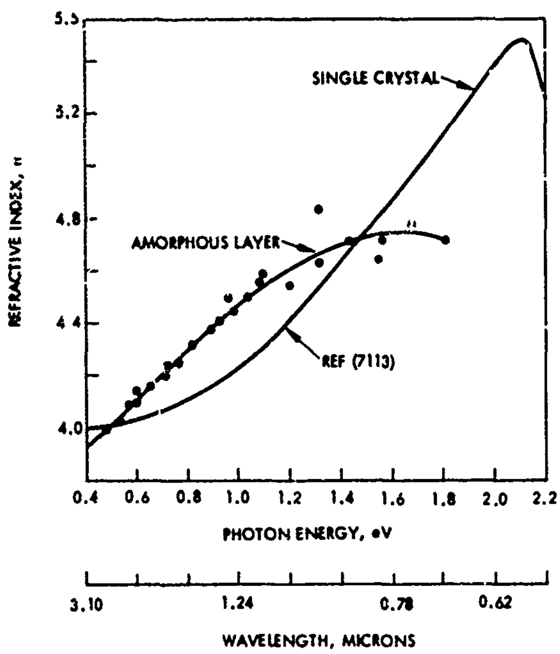
REFERENCE Brattain and Briggs (18391)

REMARKS

Figure 5-46

PARAMETER: Wavelength

MATERIAL: Germanium



FORM Film

THICKNESS Not stated mm

RAY ORDINARY ☒, EXTRAORDINARY ☐

WAVELENGTH 0.7 - 3.1 μ

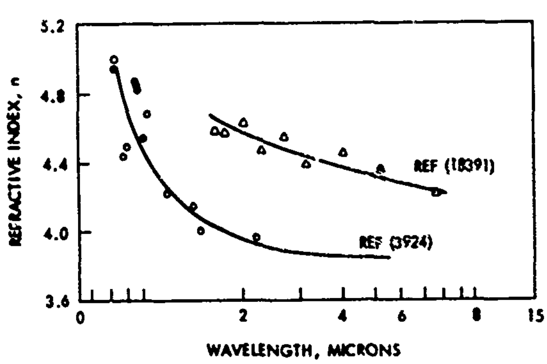
TEMPERATURE 297 °K

METHOD Transmission, Reflection

REFERENCE Tauc, et al. (22818)

REMARKS Amorphous polycrystalline layer is highly doped (10^{18} - 10^{19} cm^{-3}), and was prepared by evaporation onto a cool (300°K) quartz substrate. Crystallites are ~10^3 Å in size.

Figure 5-47



THICKNESS 1×10^{-5} mm

RAY ORDINARY ☒, EXTRAORDINARY ☐

WAVELENGTH 0.85 - 2.5 μ

TEMPERATURE ~297 °K

METHOD Transmission, Reflection

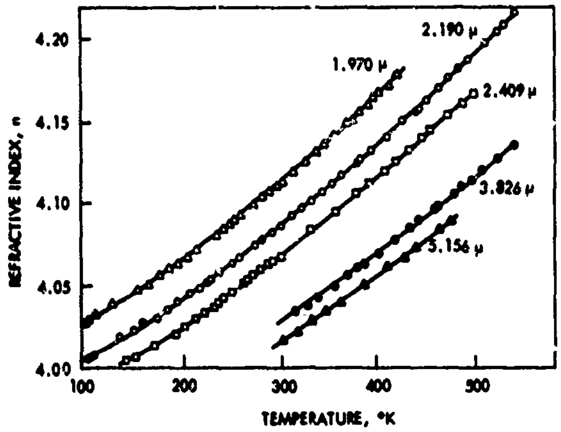
REFERENCE Lukes (3924)

REMARKS Film evaporated onto glass substrate.

Figure 5-48

PARAMETER: Temperature

MATERIAL: Germanium



FORM Bulk, Single Crystal

THICKNESS NA (Prism) mm

RAY ORDINARY ☒, EXTRAORDINARY ☐

WAVELENGTH 1.8 - 5.5 μ

TEMPERATURE 100 - 530 °K

METHOD Deviation

REFERENCE Lukes (3915)

REMARKS n-type material with resistivity = 1.2 ohm-cm. at 300°K

Figure 5-49

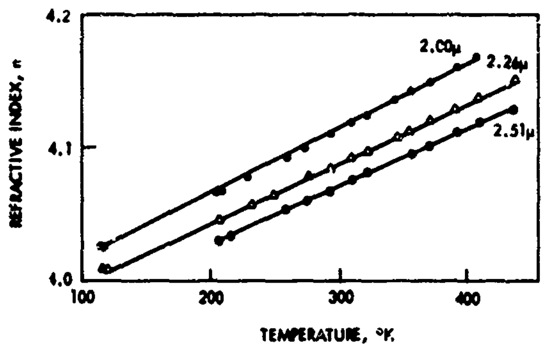
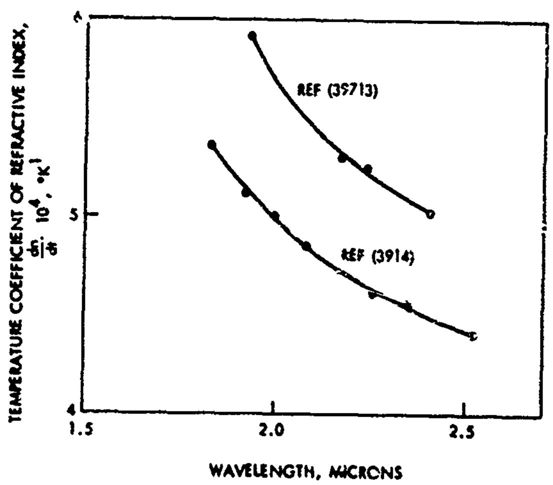


Figure 5-50



THICKNESS NA (Prism) mm

RAY ORDINARY ☒, EXTRAORDINARY ☐

WAVELENGTH 2.0 - 2.5 μ

TEMPERATURE 116 - 440 °K

METHOD Deviation

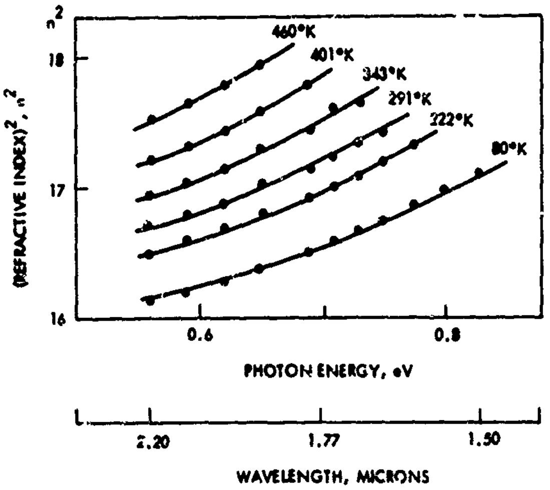
REFERENCE Lukes (3914)

REMARKS n-type germanium

Figure 5-51

PARAMETER: Temperature

MATERIAL: Germanium



FORM Bulk, Single Crystal

THICKNESS NA (Prism) mm

RAY ORDINARY ☒, EXTRAORDINARY ☐

WAVELENGTH 1.5 - 2.2 μ

TEMPERATURE 80 - 460 °K

METHOD Deviation

REFERENCE Kornfeld (14254)

REMARKS Resistivity = 50 ohm-cm.

Figure 5-52

Wavelength, (Microns)	Temperature °K	Refractive Index, n
23-40	7.5	3.98 ±0.02
45-67	7.5	3.90 ±0.02
83-143	297	3.98 ±0.02

THICKNESS 0.5 - 2.0 mm

RAY ORDINARY ☒, EXTRAORDINARY ☐

WAVELENGTH 23 - 143 μ

TEMPERATURE 7.5, 297 °K

METHOD Interference

REFERENCE Aronson, et al. (16091)

REMARKS Crystal cut perpendicular to the [111] axis.

Table 5-11

PARAMETER: Temperature

MATERIAL: Germanium

FORM Bulk, Single Crystal

THICKNESS Not stated mm

RAY ORDINARY ☒, EXTRAORDINARY ☐

WAVELENGTH 0.6 - 1.7 μ

TEMPERATURE 120, 300 °K

METHOD Reflection

REFERENCE Potter (27255)

REMARKS

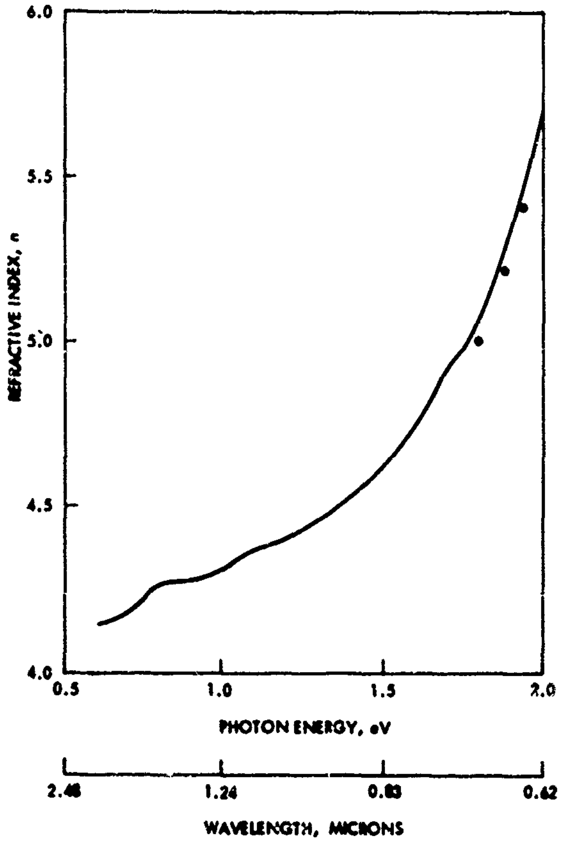


Figure 5-53

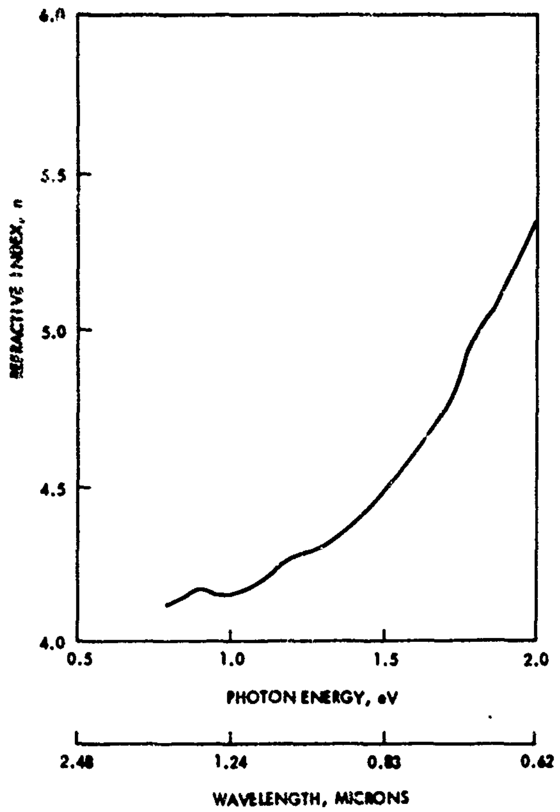
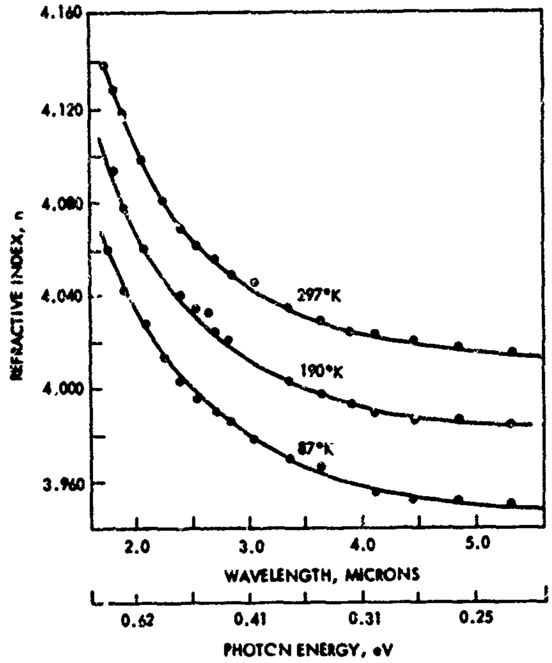


Figure 5-54

PARAMETER: Temperature

MATERIAL: Germanium



FORM Bulk

THICKNESS NA (Prism) mm

RAY ORDINARY ☒ , EXTRAORDINARY ☐

WAVELENGTH 1.8 - 5.3 μ

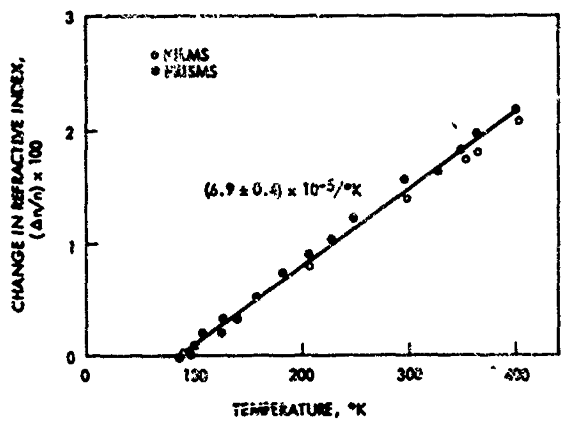
TEMPERATURE 87 - 297 °K

METHOD Deviation

REFERENCE Cardona (2569)

REMARKS

Figure 5-55



THICKNESS NA (Prism); Film mm

RAY ORDINARY ☒ , EXTRAORDINARY ☐

WAVELENGTH 3.0 μ

TEMPERATURE 90 - 400 °K

METHOD Deviation, Interference

REFERENCE Cardona, et al. (620)

REMARKS

Figure 5-56

PARAMETER: Temperature

MATERIAL: Germanium

$$dn/dT = 5.25 \times 10^{-4} (K^{\circ})^{-1}$$

FORM Not stated

THICKNESS Not stated mm

RAY ORDINARY ☒, EXTRAORDINARY ☐

WAVELENGTH 2.25 μ

TEMPERATURE Not stated °K

METHOD Not stated

REFERENCE Rochow (8766)

REMARKS

Table 5-12

Wavelength, (Microns)	Thermal Coefficient dn/dT, $(^{\circ}K)^{-1}$
1.934	5.919×10^{-4}
2.174	5.285
2.246	5.251
2.401	5.037

THICKNESS 3.0574 (single crystal) mm

RAY ORDINARY ☒, EXTRAORDINARY ☐

WAVELENGTH 2.0 - 2.4 μ

TEMPERATURE 297.5 °K

METHOD Interference

REFERENCE Rank, et al. (39713)

REMARKS Measurements in vacuo. Thermal expansion contributed only 4% to dn/dT.

Table 5-13

PARAMETER: Temperature

MATERIAL: Germanium

Wavelength, (Microns)	Refractive Index, n 77°K	300°K
8.66	3.77	3.92
9.4	3.81	3.90
10.2	3.81	3.93
11.22	3.81	3.92
12.35	3.82	3.93

FORM Film

THICKNESS 0.227 mm

RAY ORDINARY ☒ , EXTRAORDINARY ☐

WAVELENGTH 8.66 - 12.35 μ

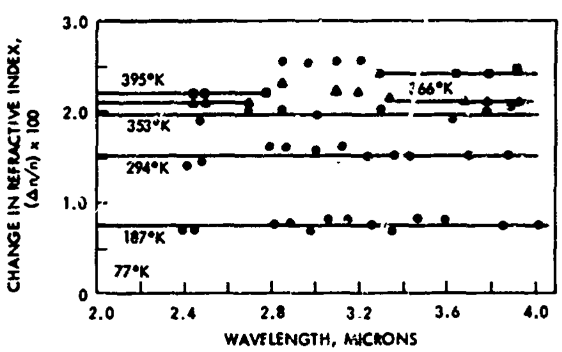
TEMPERATURE 77, 300 °K

METHOD Interference

REFERENCE Collins (40273)

REMARKS

Table 5-14



THICKNESS 1.2×10^{-2} mm

RAY ORDINARY ☒ , EXTRAORDINARY ☐

WAVELENGTH 2.0 - 4.0 μ

TEMPERATURE 77 - 395 °K

METHOD Interference

REFERENCE Cardona (2569)

REMARKS

Figure 5-57

PARAMETER: Pressure

MATERIAL: Germanium

$$(1/n)(dn/dP)_T = (-0.7 \pm 0.2) \times 10^{-6}\ cm^2 kg^{-1}$$

FORM	Film mm
THICKNESS	$(3-10) \times 10^{-3}$
RAY	ORDINARY ☒, EXTRAORDINARY ☐
WAVELENGTH	3.0 μ
TEMPERATURE	297 °K
METHOD	Interference
REFERENCE	Cardona, et al. (620)
REMARKS	Pressure range $0 - 1.42 \times 10^5$ psi

Table 5-15

$$(1/n)(dn/dP)_T = (-0.6 \pm 0.15) \times 10^{-6}\ cm^2 kg^{-1}$$

THICKNESS	Not stated mm
RAY	ORDINARY ☒, EXTRAORDINARY ☐
WAVELENGTH	~3 μ
TEMPERATURE	297 °K
METHOD	RF dielectric
REFERENCE	Cardona, et al. (620)
REMARKS	Pressure range $0 - 1.42 \times 10^5$ psi

Table 5-16

PARAMETER: Pressure

MATERIAL: Germanium

$$(1/n)(dn/dP)_T = (-0.6 \pm 0.3) \times 10^{-6}\ cm^2 kg^{-1}$$

FORM Film mm

THICKNESS 3.8×10^{-3}

RAY ORDINARY ☒, EXTRAORDINARY ☐

WAVELENGTH 2.0 - 4.0 μ

TEMPERATURE 297 °K

METHOD Interference

REFERENCE Cardona (2569)

REMARKS Pressure range $0 - 1 \times 10^5$ psi

Table 5-17

PARAMETER: Film Thickness

MATERIAL: Germanium

Film Thickness, (Microns)	Refractive Index, n
0.07	3.43
0.09	4.12
0.1	4.07
0.18	4.24
0.26	4.23
0.375	3.75
1.52	4.0
2.57	3.98
6.5	3.62

FORM Film

THICKNESS As shown mm

RAY ORDINARY ☒, EXTRAORDINARY ☐

WAVELENGTH 2.64 μ

TEMPERATURE 300 °K

METHOD Interference

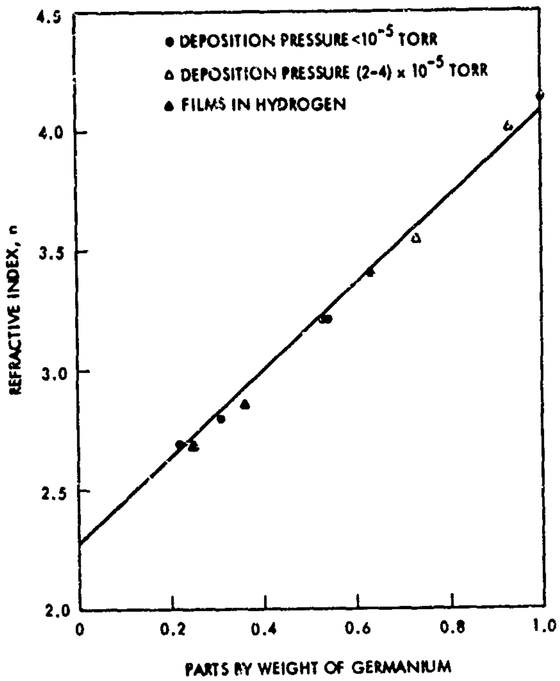
REFERENCE Wales, et al. (31497)

REMARKS Unheated substrate with electron beam heating.

Table 5-18

PARAMETER: Film Composition

MATERIAL: Germanium/ Zinc Sulfide



FORM Film, mixed (Ge + ZnS)

THICKNESS $(1.9 - 7.3) \times 10^{-4}$ mm

RAY ORDINARY ☒, EXTRAORDINARY ☐

WAVELENGTH 2.2 μ

TEMPERATURE ~298 °K

METHOD Reflection

REFERENCE Jacobsson (40180)

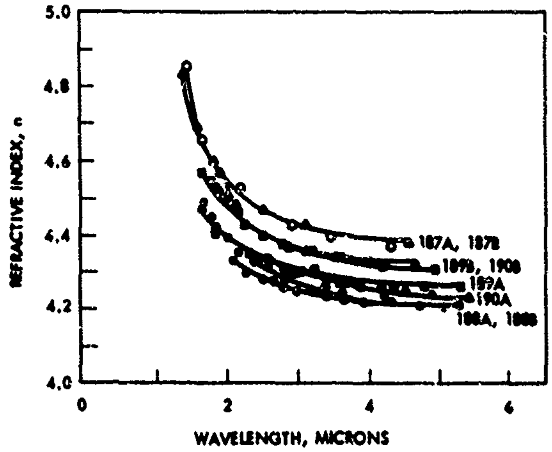
REMARKS Film produced by simultaneous evaporation from two sources.

NOTE: The absorption edge is displaced with a change in concentration, facilitating use of the film as variable cut-off filters.

Figure 5-58

PARAMETER: Film Deposition Rate

MATERIAL: Germanium



FORM Film

THICKNESS $(0.5 - 5) \times 10^{-3}$ mm

RAY ORDINARY ☒, EXTRAORDINARY ☐

WAVELENGTH 1.0 - 5.0 μ

TEMPERATURE ~300 °K

METHOD Transmission

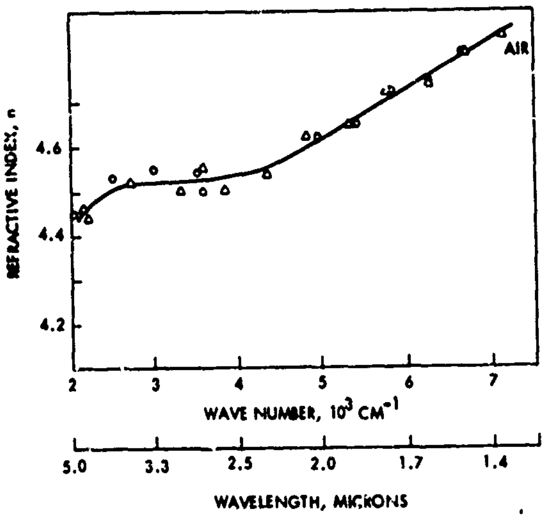
REFERENCE Wales, et al. (31497)

REMARKS Preparation on unheated substrate. Samples labelled "A" are at a higher deposition rate than "B". Source temperature is a function of number shown. "A" samples are at a higher deposition rate than "B" samples.

Figure 5-59

PARAMETER: Film Deposition Atmosphere

MATERIAL: Germanium



FORM Film

THICKNESS 10^{-3} mm

RAY ORDINARY ☒, EXTRAORDINARY ☐

WAVELENGTH 1.0 - 5.0 μ

TEMPERATURE ~297 °K

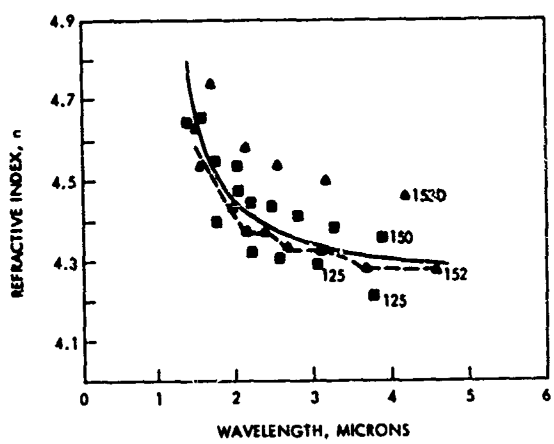
METHOD Interference, Reflection

REFERENCE Huldt and Staflin (3735)

REMARKS Glass substrate.

Layer thickness: O1.092 μ, Δ 1.010 μ.

Figure 5-60



THICKNESS (0.5 - 5) x 10^{-3} mm

RAY ORDINARY ☒, EXTRAORDINARY ☐

WAVELENGTH 1 - 5.0 μ

TEMPERATURE ~300 °K

METHOD Transmission

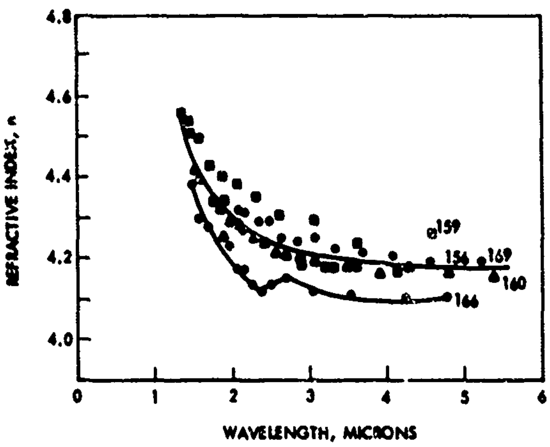
REFERENCE Wales, et al. (31497)

REMARKS Unheated substrate, electron beam heating, pressure = 1 x 10^{-6} Torr.

Figure 5-61

PARAMETER: Film Deposition Atmosphere

MATERIAL: Germanium



FORM Film

THICKNESS $(0.5 - 5) \times 10^{-3}$ mm

RAY ORDINARY ☒ , EXTRAORDINARY ☐

WAVELENGTH 1.0 - 5.0 μ

TEMPERATURE ~300 °K

METHOD Transmission

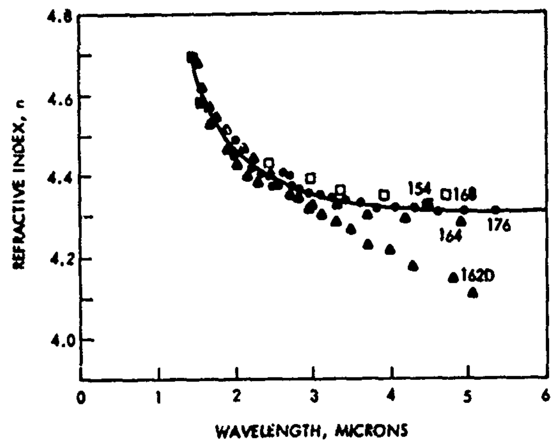
REFERENCE Wales, et al. (31497)

REMARKS Unheated substrate, electron beam heating, 1×10^{-4} Torr oxygen pressure

Figure 5-62

PARAMETER: Film Deposition Atmosphere

MATERIAL: Germanium



FORM Film

THICKNESS $(0.5 - 5) \times 10^{-3}$ mm

RAY ORDINARY ☒, EXTRAORDINARY ☐

WAVELENGTH 1.0 - 5.0 μ

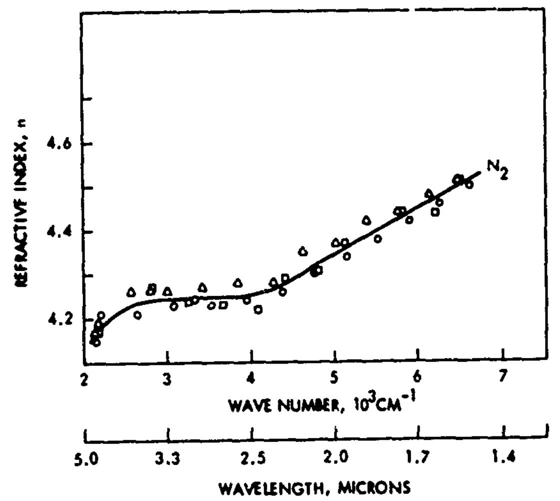
TEMPERATURE ~300 °K

METHOD Transmission

REFERENCE Wales, et al. (31497)

REMARKS Unheated substrate, electron beam heating, 1×10^{-4} Torr nitrogen pressure.

Figure 5-63



THICKNESS 10^{-3} mm

RAY ORDINARY ☒, EXTRAORDINARY ☐

WAVELENGTH 1.0 - 5.0 μ

TEMPERATURE 297 °K

METHOD Interference, Reflection

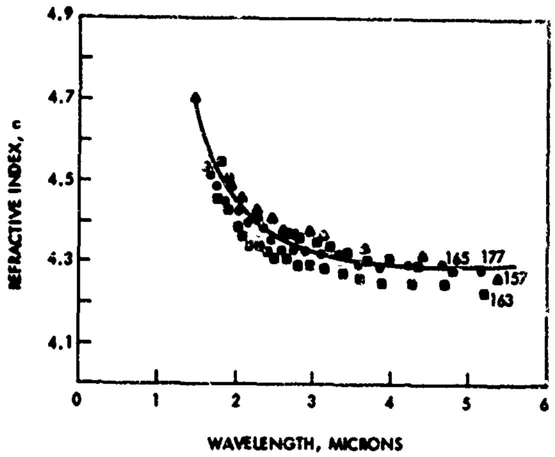
REFERENCE Huldt and Staflin (3735)

REMARKS Glass substrate. Layer thickness: ○ 1.340 μ; △ 1.364 μ; ☐ 1.449 μ.

Figure 5-64

PARAMETER: Film Deposition Atmosphere

MATERIAL: Germanium



FORM Film

THICKNESS $(0.5 - 5) \times 10^{-3}$ mm

RAY ORDINARY ☒, EXTRAORDINARY ☐

WAVELENGTH 1.0 - 5.0 μ

TEMPERATURE ~300 °K

METHOD Transmission

REFERENCE Wales, et al. (31497)

REMARKS Unheated substrate, electron beam heating, 1×10^{-4} Torr hydrogen pressure.

Figure 5-65

Film Deposition
PARAMETER: Substrate Temperature

MATERIAL: Germanium

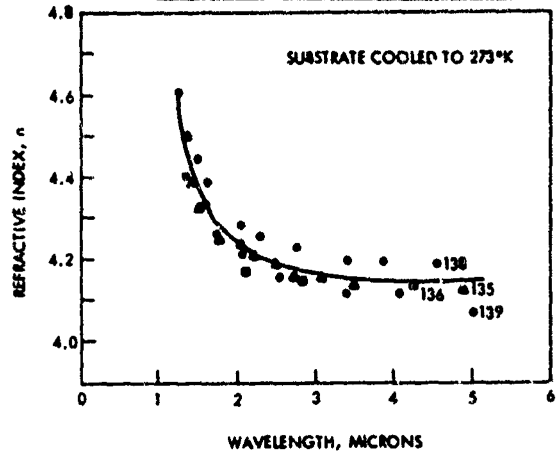


Figure 5-66
(273° K)

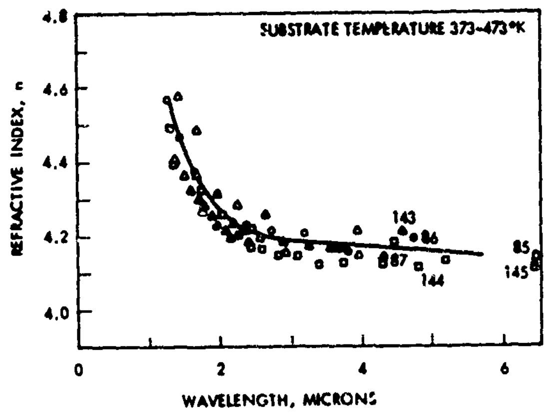


Figure 5-67
(373 - 473° K)

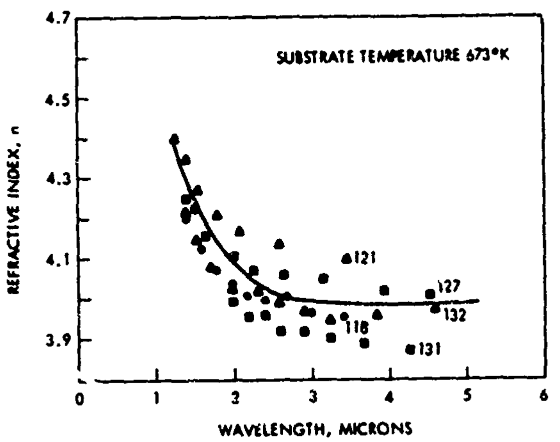


Figure 5-68
(673° K)

FORM Film

THICKNESS $(0.5 - 5) \times 10^{-3}$ mm

RAY ORDINARY ☒ , EXTRAORDINARY ☐

WAVELENGTH 1 - 5 μ

TEMPERATURE 300 °K

METHOD Transmission

REFERENCE Wales, et al. (31497)

REMARKS Substrate heated from carbon boat. Pressure = 1×10^{-6} Torr.

Figures 5-66 to 5-69

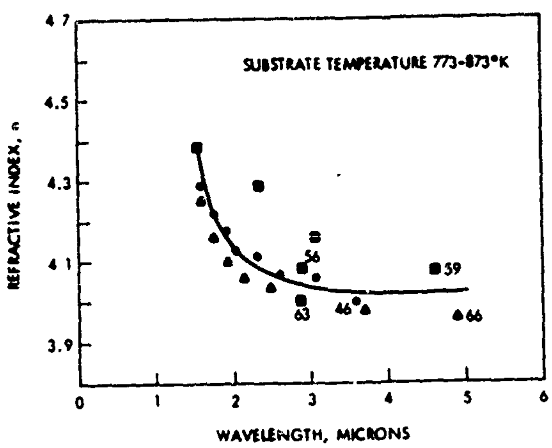
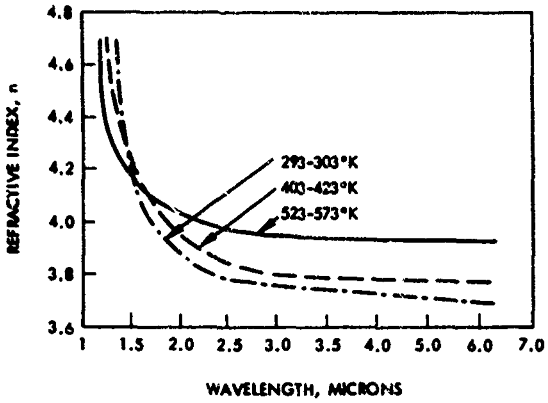


Figure 5-69
(773 - 873° K)

Film Deposition
PARAMETER: Substrate Temperature



MATERIAL: Germanium

FORM Film, amorphous and polycrystalline

THICKNESS ~1 x 10^{-3} mm

RAY ORDINARY ☒, EXTRAORDINARY ☐

WAVELENGTH 1.25 - 6.5 μ

TEMPERATURE ~298 °K

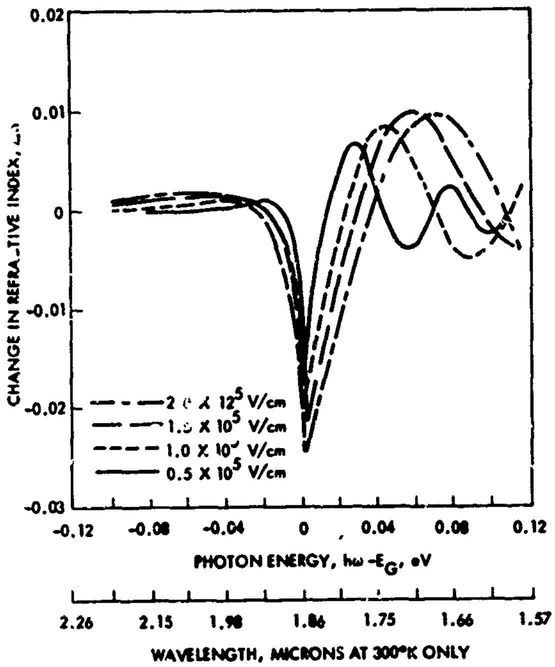
METHOD Interference

REFERENCE Gisin and Ivanov (41222)

REMARKS Evaporation of single crystal germanium of resistivity = 40 ohm-cm from graphite boat onto barium fluoride substrate at (2-5) x 10^{-5} Torr pressure.

Figure 5-70

PARAMETER: Electric Field



MATERIAL: Germanium

FORM Single Crystal pn Junction

THICKNESS Not stated mm

RAY **ORDINARY** ☒, **EXTRAORDINARY** ☐

WAVELENGTH 1.6 - 2.2 μ

TEMPERATURE 300 °K

METHOD Reflection

REFERENCE Seraphin and Bottka (38093)

REMARKS Wavelength is based on energy gap data from McFarlane, et al. (184).

Figure 5-71

ZINC SULFIDE

INTRODUCTION

Zinc sulfide occurs in two crystal forms: cubic (zincblende or sphalerite) and hexagonal (wurtzite). This semiconducting material is used in infrared optics and in luminescent devices. Single crystals for optical applications have been grown by the static vapor growth method in which powdered zinc sulfide is kept in the high temperature region. The powdered zinc sulfide is usually prepared by precipitation from aqueous solution. Highly purified zinc sulfide has a resistivity of approximately 5×10^7 ohm-cm for the hexagonal form, measured in darkness.

The physical properties of intrinsic zinc sulfide were summarizea in Table 1-1. A more complete compilation of properties is offered in Report No. S-11. Figure 1-9 shows the infrared transmission by zinc sulfide.

DATA

The data for zinc sulfide are listed in Table 5-19 and the wavelength coverage in Table 5-20. The data cover hexagonal, cubic, amorphous, and a mixture of cubic and hexagonal zinc sulfide. No data at temperatures other than room temperature were located.

Refractive index data for hexagonal zinc sulfide, single crystal material, are presented in Figures 5-72 to 5-73 and Tables 5-21 to 5-22; sinc hexagonal zinc sulfide is birefringent, plots for ordinary and extraordinary rays are included. Cubic crystal data are shown in Figures 5-74 to 5-77 and Tables 5-23 to 5-25. Figure 5-78 and Table 5-26 present data for Irtran-2, a polycrystalline material composed of 95 percent cubic and 5 percent hexagonal material Film data are provided in Figures 5-79 to 5-82 and in Table 5-27. The dependence

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of the refractive index on zinc sulfide content has been demonstrated for a germanium/zinc sulfide film in Figure 5-58.

No significant difference is observed between the bulk data for the ordinary ray on hexagonal zinc sulfide and for cubic zinc sulfide. Films tend to have a lower refractive index than bulk material.

Table 5-19. List of Zinc Sulfide Data

Figure	Table	n or k	Form	Crystal	Wavelength (Microns)		Remarks	Parameter
					From	To		
5-72		n	Bulk	Single	0.6	1.4	Hexagonal	Wavelength
	5-21	n	Bulk	Single	0.6	1.4	Hexagonal	Wavelength
5-73		n	Bulk	Single	0.3	1.6	Hexagonal	Wavelength
	5-22	n	Bulk	Single	4.0	15.0	Hexagonal	Wavelength
5-74		n	Bulk	Single	0.8	1.4	Cubic	Wavelength
	5-23	n	Bulk	Single	0.7	1.4	Cubic	Wavelength
5-75		n	Bulk	Single	0.3	4.0	Cubic	Wavelength
	5-24	n	Bulk	Single	0.7	4.0	Cubic	Wavelength
	5-25	n	Bulk	*	0.8	2.4	Cubic	Wavelength
5-76		n, k	Bulk	*	20	70	Cubic	Wavelength
5-77		n	Bulk	*	0.7	1.5	Cubic	Wavelength
5-78		n	Bulk	Polycryst**	1.0	14.0		Wavelength
	5-26	n	Bulk	Polycryst**	1.0	13.0		Wavelength
5-79		n	Film	Amorphous	0.75	2.0		Wavelength
5-80		n	Film	Amorphous	2.0	14.0		Wavelength
5-81		n	Film	*	0.4	1.2		Wavelength
5-82		n	Film	*	0.8	3.2		Wavelength
	5-27	n	Film	*	0.74	1.0		Wavelength

*Not stated

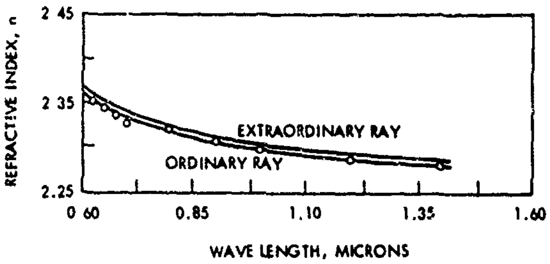
**95 percent cubic, 5 percent hexagonal (IRTRAN-2, product of Eastman-Kodak Co.)

Table 5-20. Range of Refractive Index Data for Zinc Sulfide (300° K)

Material	Range in Wavelength, Microns			
	From	To	From	To
Bulk, cubic	0.3	4.0	20	70
Bulk, hexagonal	0.3	1.6	4	15
Bulk, polycryst.	1.0	13		
Film, amorphous	0.8	14		

PARAMETER: Wavelength

MATERIAL: Zinc Sulfide



FORM Bulk, Single Crystal, Hexagonal

THICKNESS NA (prism) mm

RAY ORDINARY ☒ , EXTRAORDINARY ☒

WAVELENGTH 0.6 - 1.4 μ

TEMPERATURE ~298 °K

METHOD Deviation

REFERENCE Bieniewsky & Czyzak(8761)

REMARKS

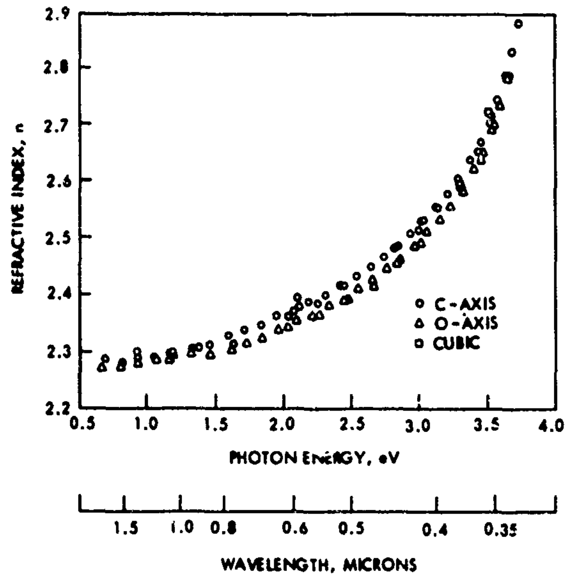
Figure 5-72

Wavelength, (Microns)	Refractive Index, n	
	Extraordinary Ray	Ordinary Ray
0.600	2.368	2.363
6.625	2.358	2.354
0.6500	2.350	2.346
0.6750	2.343	2.339
0.7000	2.337	2.332
0.8000	2.328	2.324
0.9000	2.315	2.310
1.0000	2.303	2.301
1.2000	2.294	2.290
1.4000	2.288	2.285

Table 5-21

PARAMETER: Wavelength

MATERIAL: Zinc Sulfide



FORM Bulk, Single Crystal, Hexagonal

THICKNESS 5×10^{-3} mm

RAY ORDINARY ☒, EXTRAORDINARY ☒

WAVELENGTH 0.3 - 1.6; 4 - 15 μ

TEMPERATURE 293 °K

METHOD Interference

REFERENCE Piper, et al. (735)

REMARKS

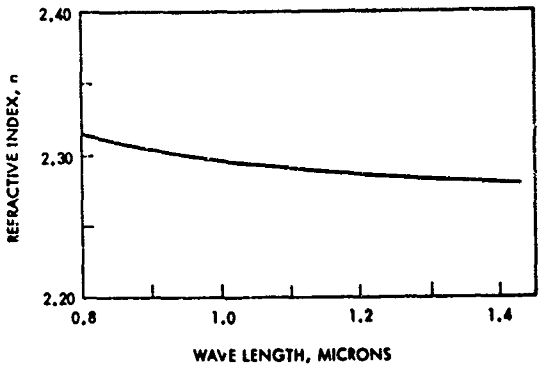
Figure 5-73

Wavelength, (Microns)	Refractive Index, n
4 - 15	2.26 ± 0.06

Table 5-22

PARAMETER: Wavelength

MATERIAL: Zinc Sulfide



FORM Bulk, Single Crystal, Cubic mm

THICKNESS NA (prism)

RAY ORDINARY ☒, EXTRAORDINARY ☐

WAVELENGTH 0.7 - 1.4 μ

TEMPERATURE ~298 °K

METHOD Deviation

REFERENCE Czyzak, et al. (6331)

REMARKS

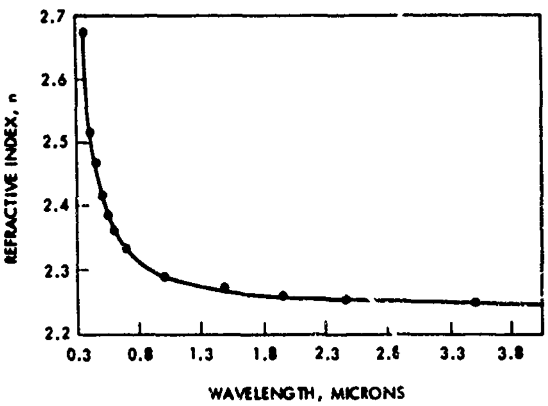
Figure 5-74

Wavelength, (Microns)	Refractive Index, n	
	Calculated	Observed
0.700	2.332	2.334
0.900	2.303	2.306
1.050	2.293	2.293
1.200	2.285	2.282
1.400	2.280	2.284

Table 5-23

PARAMETER: Wavelength

MATERIAL: Zinc Sulfide



FORM Bulk, Single Crystal, Cubic

THICKNESS NA (Prism) mm

RAY ORDINARY ☒, EXTRAORDINARY ☐

WAVELENGTH 0.3 - 4.0 μ

TEMPERATURE ~298 °K

METHOD Deviation

REFERENCE Czyzak, et al. (14914)

REMARKS

Figure 5-75

Wavelength, (Microns)	Refractive Index, n	
	Calculated	Measured
0.700	2.329	2.332
1.000	2.292	2.293
1.500	2.270	2.275
2.000	2.260	2.263
2.500	2.256	2.256
3.000	2.253	2.253
3.500	2.251	2.251
4.000	2.250	2.251

THICKNESS NA (Prism) mm

RAY ORDINARY ☒, EXTRAORDINARY ☐

WAVELENGTH 0.7 - 4.0 μ

TEMPERATURE ~298 °K

METHOD Deviation

REFERENCE Czyzak, et al. (14914)

REMARKS

Table 5-24

PARAMETER: Wavelength

MATERIAL: Zinc Sulfide

Wavelength, (Microns)	Refractive Index, n
0.8	2.3146
0.9	2.3026
1.0	2.2932
1.2	2.2822
1.4	2.2762
1.6	2.2716
1.8	2.2680
2.0	2.2653
2.2	2.2637
2.4	2.2604

FORM Bulk, Cubic mm

THICKNESS NA (Prism)

RAY ORDINARY ☒, EXTRAORDINARY ☐

WAVELENGTH 0.8 - 2.4 μ

TEMPERATURE ~298 °K

METHOD Deviation

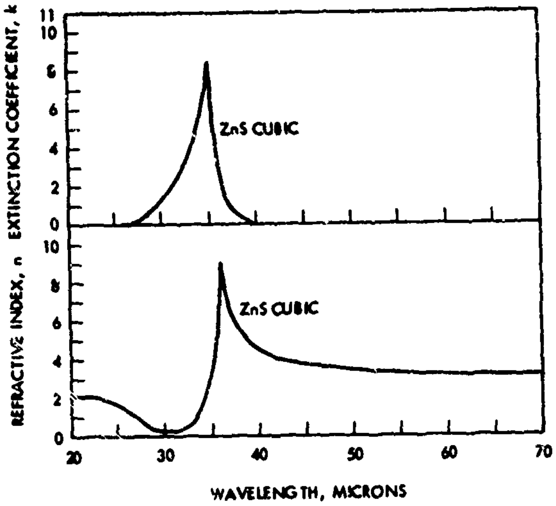
REFERENCE Bond (19989)

REMARKS Natural crystal from Spain

Table 5-25

PARAMETER: Wavelength

MATERIAL: Zinc Sulfide



FORM Bulk, Cubic

THICKNESS Not Stated mm

RAY ORDINARY ☒ , EXTRAORDINARY ☐

WAVELENGTH 20 - 70 μ

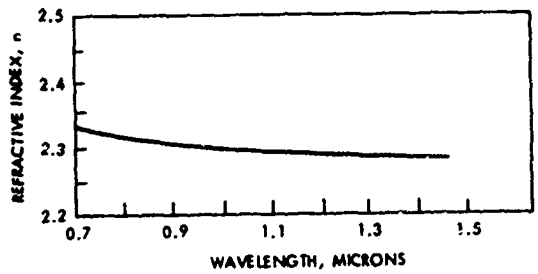
TEMPERATURE 300 °K

METHOD Reflection

REFERENCE Manabe (28526)

REMARKS Natural crystal

Figure 5-76



THICKNESS NA (Prism) mm

RAY ORDINARY ☒ , EXTRAORDINARY ☐

WAVELENGTH 0.7 - 1.5 μ

TEMPERATURE ~298 °K

METHOD Deviation

REFERENCE DeVore (40276)

REMARKS Sphalerite, natural crystal

Figure 5-77

PARAMETER: Wavelength

MATERIAL: Zinc Sulfide

FORM Bulk, Polycrystalline

THICKNESS Not Stated mm

RAY ORDINARY ☒ , EXTRAORDINARY ☒

WAVELENGTH 1.0 - 14.0 μ

TEMPERATURE ~298 °K

METHOD Not Stated

REFERENCE Kodak [1967]

REMARKS IRTRAN-2 material

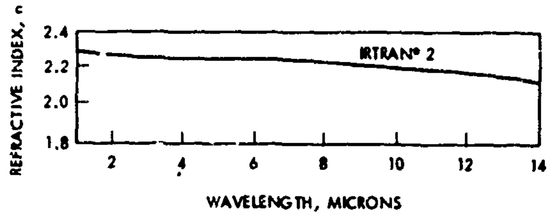


Figure 5-78

Table 5-26

Wavelength, (Microns)	Refractive Index n	Wavelength, (Microns)	Refractive Index, n
1.0000	2.2907	6.0000	2.2381
1.2500	2.2777	6.2500	2.2363
1.5000	2.2706	6.5000	2.2344
1.7500	2.2662	6.7500	2.2324
2.0000	2.2631	7.0000	2.2304
2.2500	2.2608	7.2500	2.2282
2.5000	2.2589	7.5000	2.2260
2.7500	2.2573	7.7500	2.2237
3.0000	2.2558	8.0000	2.2213
3.2500	2.2544	8.2500	2.2188
3.5000	2.2531	8.5000	2.2162
3.7500	2.2518	8.7500	2.2135
4.0000	2.2504	9.0000	2.2107
4.2500	2.2491	9.2500	2.2078
4.5000	2.2477	9.5000	2.2048
4.7500	2.2462	9.7500	2.2018
5.0000	2.2447	10.0000	2.1986
5.2500	2.2432	11.0000	2.1846
5.5000	2.2416	12.0000	2.1688
5.7500	2.2399	13.0000	2.1508

PARAMETER: Wavelength

MATERIAL: Zinc Sulfide

FORM Film, Amorphous

THICKNESS $(1\text{-}4) \times 10^{-3}$ mm

RAY ORDINARY ☒, EXTRAORDINARY ☐

WAVELENGTH 0.75 - 14 μ

TEMPERATURE ~298 °K

METHOD Transmission, Reflection

REFERENCE Hall & Ferguson (2609)

REMARKS Vapor-deposited film-
0.75 - 2 micron data on glass substrate, 2 - 14 microns on rock salt substrate

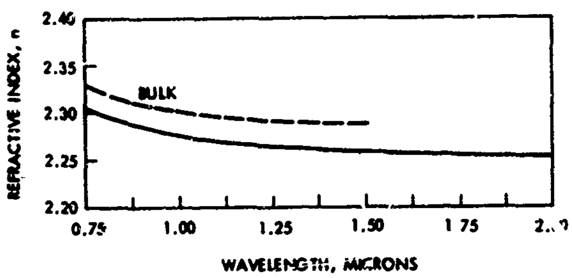


Figure 5-79

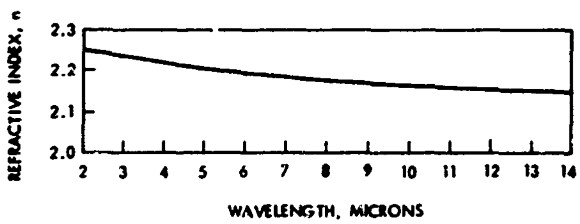
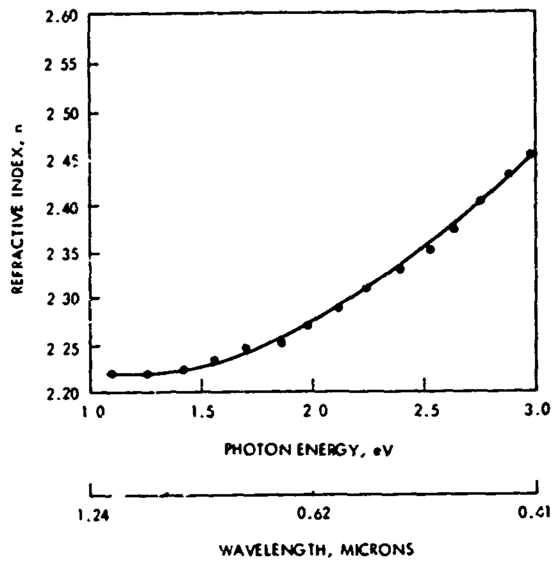


Figure 5-80

PARAMETER: Wavelength

MATERIAL: Zinc Sulfide



FORM Film

THICKNESS Not stated mm

RAY ORDINARY ☒, EXTRAORDINARY ☐

WAVELENGTH 0.4 - 1.2 μ

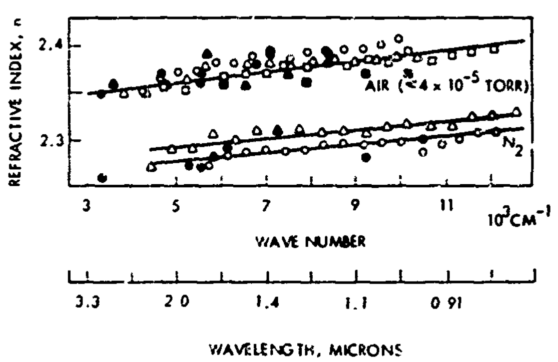
TEMPERATURE ~298 °K

METHOD Interference

REFERENCE Burgiel, et al. (34617)

REMARKS Sputtered and evaporated films used with identical results. Sputtered film was predominantly cubic.

Figure 5-81



Air plots: O, layer with d = 2.500μ, Δ, d = 2.221μ; ☐, d = 2.258μ. Nitrogen plots: O, layer with d = 2.501μ, Δ, d = 2.233μ. + determined by calculation. x determined from Brewster angle; remaining plots from geometrical thickness of film.

THICKNESS 2.5×10^{-3} mm

RAY ORDINARY ☒, EXTRAORDINARY ☐

WAVELENGTH 0.8 - 3.2 μ

TEMPERATURE ~298 °K

METHOD Interference

REFERENCE Huldt & Staflin (3735)

REMARKS Evaporation onto glass substrate in atmosphere of air or nitrogen.

Figure 5-82

PARAMETER: Wavelength

MATERIAL: Zinc Sulfide

Wavelength, (Microns)	Refractive Index, n	Extinction Coefficient, k
0.740	2.30	0.000
0.900	2.23	0.000
0.980	2.27	0.000

FORM Film

THICKNESS 3×10^{-4} mm

RAY ORDINARY ☒, EXTRAORDINARY ☐

WAVELENGTH 0.74 - 1.0 μ

TEMPERATURE ~298 °K

METHOD Transmission, Reflection

REFERENCE Kuwabara & Isiguro (40442)

REMARKS Film evaporated onto glass substrate at ~10^{-4} Torr.

Table 5-27

CADMIUM TELLURIDE

INTRODUCTION

Cadmium telluride is a semiconductor that has found application in infrared optics and semiconductor devices including solar cells. This material may show both n- and p type conduction; addition of excess cadmium gives n-type conduction and conversely, addition of excess tellurium gives p-type conduction.

Cadmium telluride is usually prepared from electrolytic cadmium and vacuum-distilled tellurium by direct combination at an elevated temperature under a nitrogen atmosphere. Zone refining is used for further purification. The electrical and optical properties are strongly affected by deviation from the stochiometric ratio of the components (cadmium and tellurium). Details concerning the equilibrium phase diagram for cadmium telluride may be located in EPIC Data Sheet DS-157. The electrical resistivity of highly pure single crystal cadmium telluride at room temperature is approximately 10^7 ohm-cm. The optical transmission by cadmium telluride is shown in Figures 1-9 and 1-10.

The physical properties of cadmium telluride were summarized in Table 1-1.

EPIC Report S-11 provides additional property data on cadmium telluride. As with other semiconductors, different doping levels in authors' reports make it often difficult to compare their results.

DATA

All data presentations for cadmium telluride are listed in Table 5-28 and a summary of wavelength and temperature coverage is plotted in Figure 5-83. Figures 5-84 to Figure 5-88 and Tables 5-29 to 5-31 represent refractive index spectra for bulk single crystal material. Below five microns, the pure or lightly n-doped materials show no wide differences in refractive index. At longer wavelengths the data exhibit a far wider spread between the author's data and it

would he difficult to recommend a "best" set of values. Heavily n-doped materials are represented by data in Figures 5-89, 5-90 and 5-91. The data in Tables 5-32 to 5-34 and Figure 5-90 and 5-91, could not be identified regarding their crystalline status (e.g., single crystal) but, except for heavily doped materials, they show no marked departure from the spread for single crystals.

Figures 5-92 to 5-95 and Tables 5-35 to 5-37 cover polycrystalline materials and the data are similar to those obtained from single crystal material of a similar doping level.

The temperature dependence of the refractive index is the subject of Tables 5-38 to 5-39 and Figures 5-96 to 5-101. The relative sparsity of such data does not permit any generalization.

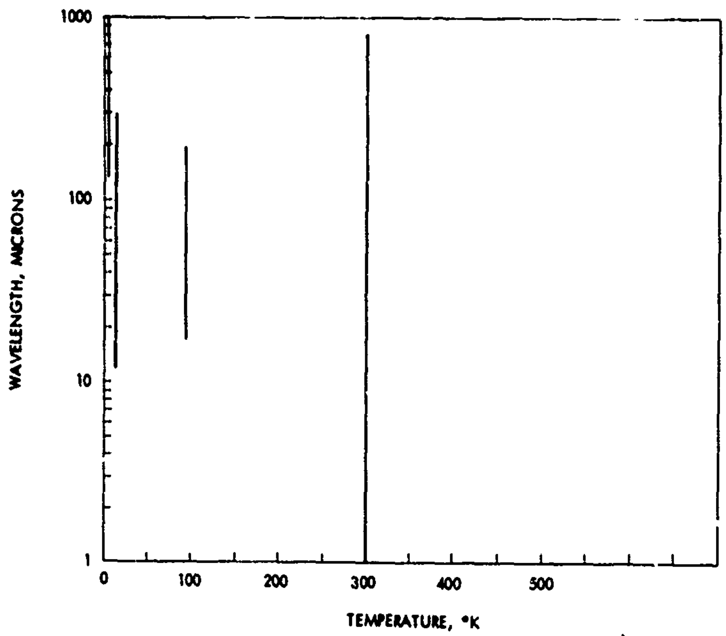


Figure 5-83. Wavelength and Temperature Range for Cadmium Telluride Data

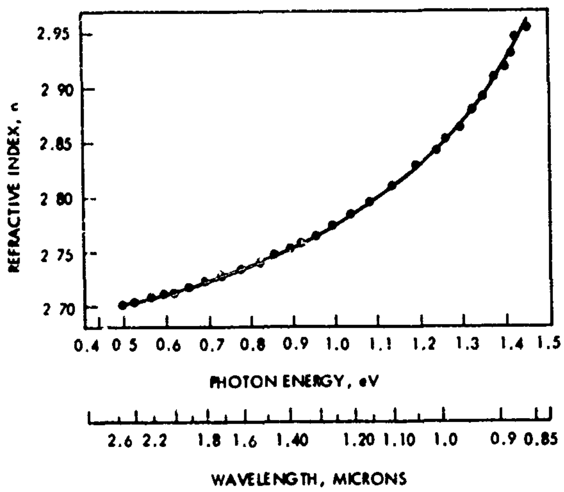
Table 5-28. List of Cadmium Telluride Data

Figure	Table	n or k	Form	Crystal	Wavelength, (Microns) From	To	Remarks	Parameter
5-84		n	Bulk	Single	0.085	2.6		Wavelength
	5-29	n	Bulk	Single	2.0	10.0		Wavelength
5-85		n	Bulk	Single	12.5	300	8, 300°K	Wavelength
5-86		n	Bulk	Single	133	1000	4.2°K	Wavelength
5-87		n, k	Bulk	Single	37	85	100, 300°K	Wavelength
5-88		n	Bulk	Single	5.0	10.0		Wavelength
	5-30	n	Bulk	Single	0.87	1.00	n-type 293°, 373°K	Wavelength
5-89		n	Bulk	Single	6.5	14.5	n-type, heavily doped	Wavelength
	5-31	n	Bulk	Single	0.90	1.1	n-type	Wavelength
	5-32	n	Bulk	*	2.5	2.5	n-type	Wavelength
	5-33	n	Bulk	*	8.0	14.0	n-type	Wavelength
	5-34	n	Bulk	*	10.0	10.0	n-type	Wavelength
5-90		n, k	Bulk	*	20	200	n-type, heavily doped 100°K	Wavelength
5-91		n, k	Bulk	*	20	200	n-type, heavily doped 300°K	Wavelength
5-92		n	Bulk	Polycryst.	1.0	16.0		Wavelength
	5-35	n	Bulk	Polycryst.	1.0	16.0		Wavelength
5-93		n, k	Bulk	Polycryst.	50	75	90°K	Wavelength
5-94		n, k	Bulk	Polycryst	55	78	300°K	Wavelength
5-95		n	Bulk	Polycryst.	220	1000		Wavelength
	5-36	n	Bulk	Polycryst.	1.0	10.0		Wavelength
	5-37	n	Bulk	Polycryst.	23	28	n-type	Wavelength
	5-38	n	Bulk	Single	0.87	1.00	n-type, 293, 373°K	Temperature
5-96		n	Bulk	Single	37	85	100, 300°K	Temperature
5-97		n	Bulk	*	20	200	n-type, 100°K	Temperature
5-98		n	Bulk	*	20	200	n-type, 300°K	Temperature
5-99		n	Bulk	*	12.5	300	8°, 300°K	Temperature
5-100		n	Bulk	Polycryst.	50	75	90°K	Temperature
5-101		n	Bulk	Polycryst.	55	78	300°K	Temperature
	5-39	$1/n(\frac{dn}{dT})$	Bulk	Single	10.6	10.6	293 - 318°K	Temperature

*Not Stated

PARAMETER: Wavelength

MATERIAL: Cadmium Telluride



FORM Bulk, Single Crystal

THICKNESS NA (Prism) mm

RAY ORDINARY ☒, EXTRAORDINARY ☐

WAVELENGTH 0.085 - 2.6 μ

TEMPERATURE ~298 °K

METHOD Deviation

REFERENCE Marple (15085)

REMARKS Material grown from melt containing < 10 ppm total impurities.

Figure 5-84

Wavelength, (Microns)	Refractive Index, n
2.0	2.710
3.0	2.694
4.0	2.687
5.0	2.680
6.0	2.675
8.0	2.669
10.0	2.658

THICKNESS NA (Prism) mm

RAY ORDINARY ☒, EXTRAORDINARY ☐

WAVELENGTH 2 - 10 μ

TEMPERATURE ~298 °K

METHOD Deviation

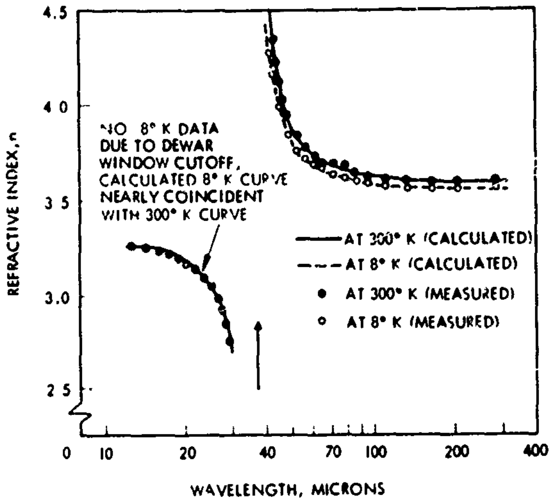
REFERENCE Vitrikhovskiy (31017)

REMARKS

Table 5-29

PARAMETER: Wavelength

MATERIAL: Cadmium Telluride



FORM Bulk

THICKNESS 0.172 mm

RAY ORDINARY ☒ , EXTRAORDINARY ☐

WAVELENGTH 12.5 - 300 μ

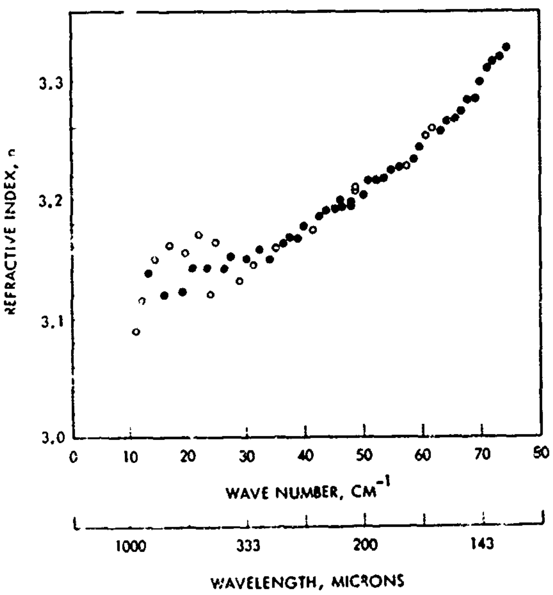
TEMPERATURE 8, 300 °K

METHOD Interference

REFERENCE Johnson, et al. (40781)

REMARKS Resistivity = 8.5x10^5 ohm-cm.

Figure 5-85



THICKNESS 1.22 mm

RAY ORDINARY ☒ , EXTRAORDINARY ☐

WAVELENGTH 133 - 100 μ

TEMPERATURE 4.2 °K

METHOD Interference

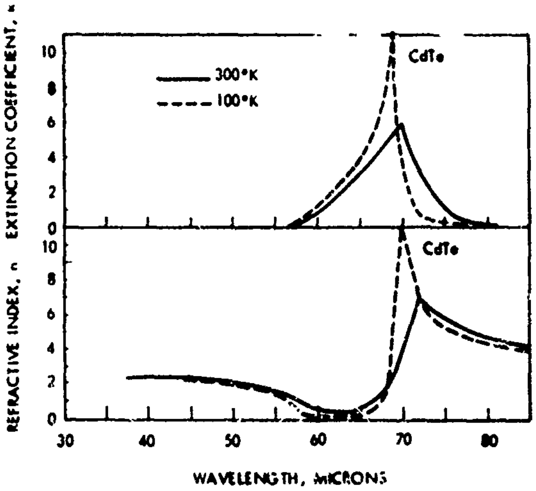
REFERENCE Halsted, et al. (26678)

REMARKS

Figure 5-86.

PARAMETER: Wavelength

MATERIAL: Cadmium Telluride



FORM Bulk, Single Crystal

THICKNESS Not stated mm

RAY ORDINARY ☒, EXTRAORDINARY ☐

WAVELENGTH 37 - 85 μ

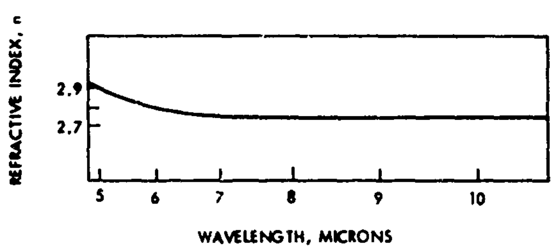
TEMPERATURE 100, 300 °K

METHOD Reflection

REFERENCE Manabe, et al. (28526)

REMARKS

Figure 5-87



THICKNESS Not stated mm

RAY ORDINARY ☒, EXTRAORDINARY ☐

WAVELENGTH 5 - 10 μ

TEMPERATURE 300 °K

METHOD Reflection

REFERENCE De Nobel (306)

REMARKS

Figure 5-88

PARAMETER: Wavelength

MATERIAL: Cadmium Telluride

Temperature, °K	Wavelength, (Microns)	Refractive Index, n
293	0.865	3.50 max.
293	0.900	3.20
293	1.000	2.80
373	0.872	3.40 max.
373	0.900	3.15
373	1.000	3.20

FORM Bulk, Single Crystal

THICKNESS 0.1 mm

RAY ORDINARY ☒, EXTRAORDINARY ☐

WAVELENGTH 0.87 - 1.00 μ

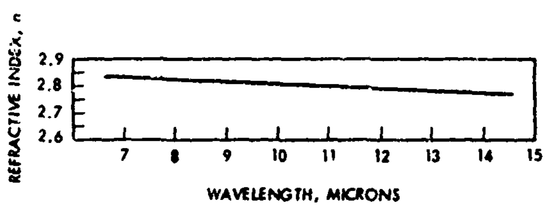
TEMPERATURE ~298 °K

METHOD Reflection, Transmission

REFERENCE Konak (11590)

REMARKS n-type material, resistivity $\approx 10^5$ ohm-cm

Table 5-30



THICKNESS 0.63, 1.10 mm

RAY ORDINARY ☒, EXTRAORDINARY ☐

WAVELENGTH 6.5 - 14.5 μ

TEMPERATURE ~298 °K

METHOD Reflection

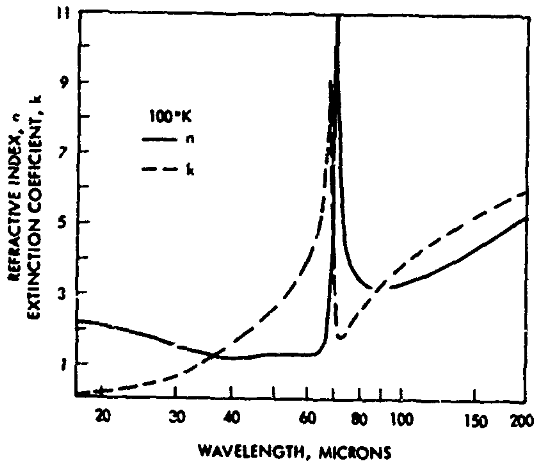
REFERENCE Planker & Kauer (40526)

REMARKS n-type material, Gallium concentration $\sim 5 \times 10^{17}$ cm^{-3}

Figure 5-89

PARAMETER: Wavelength

MATERIAL: Cadmium Telluride



FORM Bulk

THICKNESS Not stated mm

RAY ORDINARY ☒, EXTRAORDINARY ☐

WAVELENGTH 20 - 200 μ

TEMPERATURE 100, 300 °K

METHOD Reflection

REFERENCE Manabe, et al. (36435)

REMARKS n-type material, indium-doped, carrier concentration = 5.25×10^{17} cm^{-3} at 300°K, resistivity = 1.92×10^{-2} ohm-cm at 300°K.

Figure 5-90

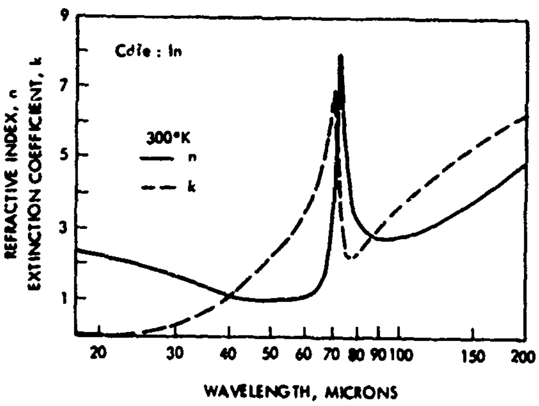


Figure 5-91

PARAMETER: Wavelength

MATERIAL: Cadmium Telluride

Wavelength, (Microns)	Refractive Index, n
0.903	3.47 ± 0.05
1.100	3.13 ± 0.04

FORM Bulk, single crystal

THICKNESS 1.0 mm

RAY ORDINARY ☒, EXTRAORDINARY ☐

WAVELENGTH 0.90, 1.10 μ

TEMPERATURE ~298 °K

METHOD Not stated

REFERENCE Garlick, et al. (7771)

REMARKS n-type, indium-doped, concentration not stated.

Table 5-31

Wavelength, Microns	Refractive Index, n
2.5	2.70

THICKNESS 4.0 mm

RAY ORDINARY ☒, EXTRAORDINARY ☐

WAVELENGTH 2.5 μ

TEMPERATURE ~298 °K

METHOD Reflectance

REFERENCE Marple (10559)

REMARKS Pure n-type material with carrier concentration $= 6 \times 10^{14}$ cm^{-3}

Table 5-32

PARAMETER: Wavelength

MATERIAL: Cadmium Telluride

Wavelength, (Microns)	Refractive Index, n
8-14	2.67

FORM Bulk

THICKNESS Not stated mm

RAY ORDINARY ☒ , EXTRAORDINARY ☐

WAVELENGTH 8 - 14 μ

TEMPERATURE 298 °K

METHOD Interference

REFERENCE Fisher & Fan (5400)

REMARKS n-type material with electron concentration ~ 1×10^{15} cm^{-3}

Table 5-33

Wavelength, (Microns)	Refractive Index, n
10	2.61

THICKNESS Not stated mm

RAY ORDINARY ☒ , EXTRAORDINARY ☐

WAVELENGTH 10 μ

TEMPERATURE ~298 °K

METHOD Interference

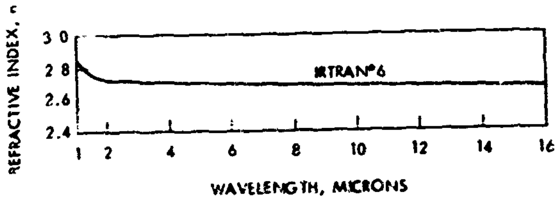
REFERENCE Davis & Shilliday (3648)

REMARKS Pure n-type material with carrier concentration ~1×10^{15} cm^{-3}

Table 5-34

PARAMETER: Wavelength

MATERIAL: Cadmium Telluride



FORM Bulk, polycrystalline

THICKNESS Not stated mm

RAY ORDINARY ☒ EXTRAORDINARY ☐

WAVELENGTH 1.0 - 16 μ

TEMPERATURE 298 °K

METHOD Not stated

REFERENCE Kodak (1967)

REMARKS

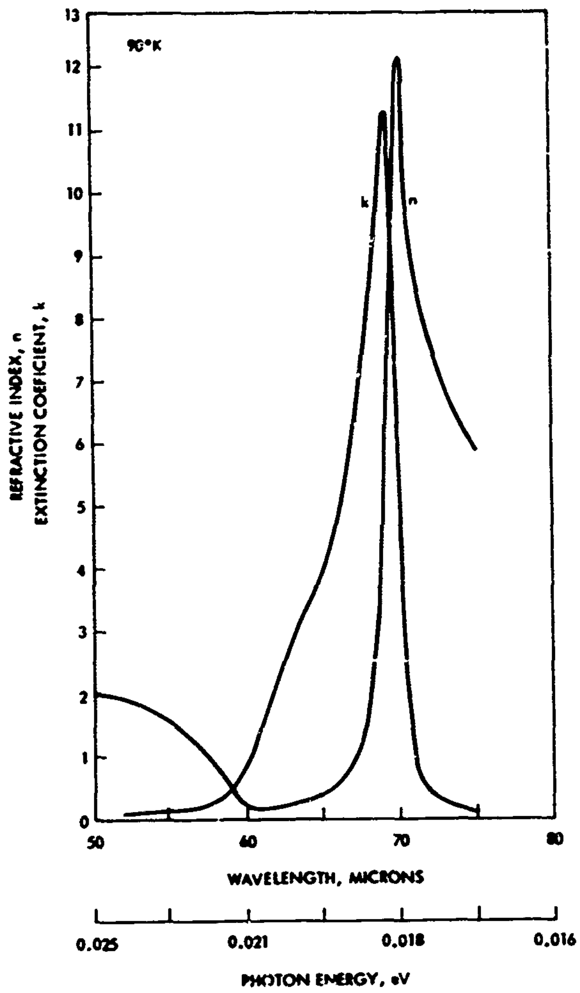
Figure 5-92

Wavelength, (Microns)	Refractive Index, n	Wavelength, (Microns)	Refractive Index, n
1.0000	2.838	6.2500	2.681
1.2500	2.773	6.5000	2.680
1.5000	2.742	6.7500	2.680
1.7500	2.725	7.0000	2.679
2.0000	2.714	7.2500	2.678
2.2500	2.707	7.5000	2.678
2.5000	2.702	7.7500	2.677
2.7500	2.698	8.0000	2.677
3.0000	2.695	8.2500	2.676
3.2500	2.693	8.5000	2.675
3.5000	2.691	8.7500	2.675
3.7500	2.689	9.0000	2.674
4.0000	2.688	9.2500	2.674
4.2500	2.687	9.5000	2.673
4.5000	2.686	9.7500	2.672
4.7500	2.685	10.0000	2.672
5.0000	2.684	11.0000	2.669
5.2500	2.683	12.0000	2.666
5.5000	2.683	13.0000	2.663
5.7500	2.682	14.0000	2.660
6.0000	2.681	15.0000	2.657
		16.0000	2.655

Table 5-35

PARAMETER: Wavelength

MATERIAL: Cadmium Telluride



FORM Bulk, Polycrystalline mm

THICKNESS Not stated

RAY ORDINARY ☒, EXTRAORDINARY ☐

WAVELENGTH 50 - 78 μ

TEMPERATURE 90, 300 °K

METHOD Reflection

REFERENCE Mitsuishi (481)

REMARKS

Figure 5-93

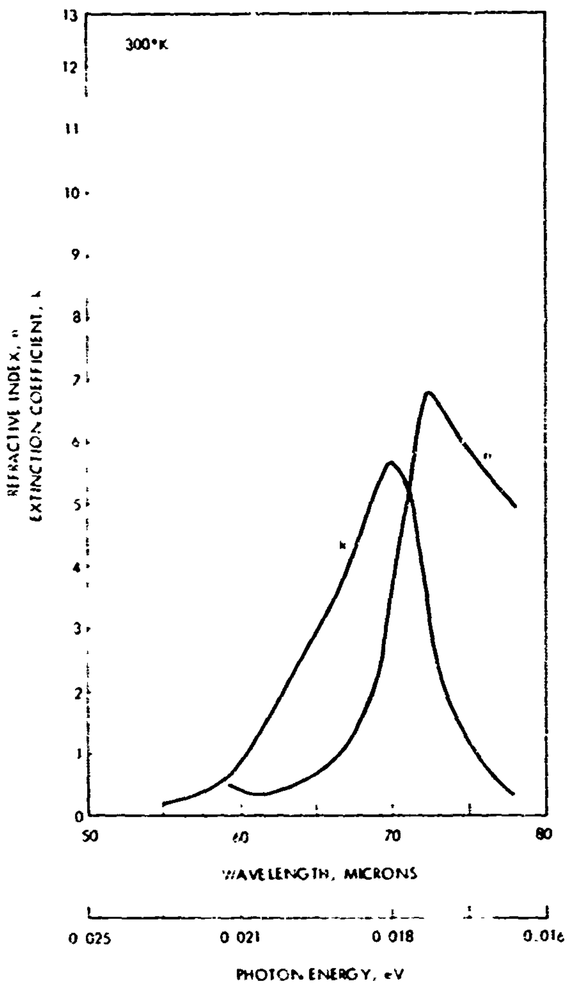

300°K
REFRACTIVE INDEX, n
EXTINCTION COEFFICIENT, k
n
k
13
12
11
10
9
8
7
6
5
4
3
2
1
0
50
60
70
80
WAVELENGTH, MICRONS
0.025
0.021
0.018
0.016
PHOTON ENERGY, eV

Figure 5-94

PARAMETER: Wavelength

MATERIAL: Cadmium Telluride

FORM Bulk, polycrystalline

THICKNESS 1 - 3 mm

RAY ORDINARY ☒ , EXTRAORDINARY ☐

WAVELENGTH 23.3 - 28 μ

TEMPERATURE ~298 °K

METHOD Interference

REFERENCE Lorimor & Spitzer (20784)

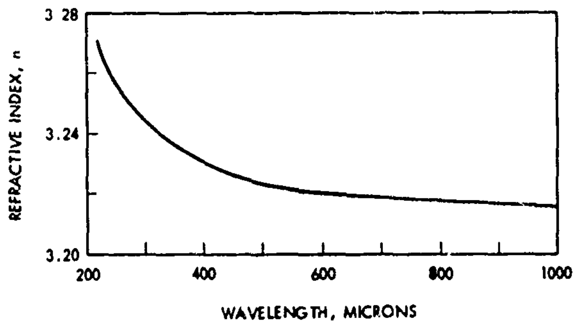
REMARKS Pure, n-type with carrier concentration ~ 1×10^{15} cm^{-3} at 298°K

Wavelength, (Microns)	Refractive Index, n
23.35	2.58
27.95	2.53

Table 5-37

PARAMETER: Wavelength

MATERIAL: Cadmium Telluride



FORM Bulk, Polycrystalline

THICKNESS Not stated mm

RAY ORDINARY ☒, EXTRAORDINARY ☐

WAVELENGTH 220 - 1000 μ

TEMPERATURE ~298 °K

METHOD Interference

REFERENCE Randall & Rawcliffe(33290)

REMARKS IRTRAN-6 material

Figure 5-95

Wavelength, (Microns)	Refractive index, n
1.0	2.839
1.5	2.742
2.0	2.713
2.5	2.702
3.0	2.695
3.5	2.691
4.0	2.688
5.0	2.684
6.0	2.681
7.0	2.679
8.0	2.677
9.0	2.674
10.0	2.672

THICKNESS NA (Prism) mm

RAY ORDINARY ☒, EXTRAORDINARY ☐

WAVELENGTH 1.0 - 10 μ

TEMPERATURE 298 °K

METHOD Deviation

REFERENCE Ladd (27063)

REMARKS ITRAN-6 material

Table 5-36

PARAMETER: Temperature

MATERIAL: Cadmium Telluride

Temperature, °K	Wavelength, (Microns)	Refractive Index, n
293	0.865	3.50 max.
293	0.900	3.20
293	1.000	2.80
373	0.872	3.40 max.
373	0.900	3.15
373	1.000	3.20

FORM Bulk, Single Crystal

THICKNESS 0.1 mm

RAY ORDINARY ☒, EXTRAORDINARY ☐

WAVELENGTH 0.87 - 1.00 μ

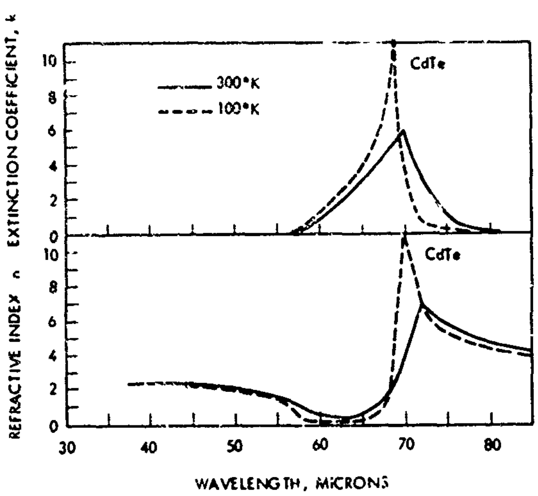
TEMPERATURE ~298 °K

METHOD Reflection, Transmission

REFERENCE Konak (11590)

REMARKS n-type material, resistivity ≅ 10^5 ohm-cm

Table 5-38



THICKNESS Not stated mm

RAY ORDINARY ☒, EXTRAORDINARY ☐

WAVELENGTH 37 - 85 μ

TEMPERATURE 100, 300 °K

METHOD Reflection

REFERENCE Manabe, et al (28526)

REMARKS

Figure 5-96

PARAMETER: Temperature

MATERIAL: Cadmuim Telluride

FORM Bulk

THICKNESS Not stated mm

RAY ORDINARY ☒ , EXTRAORDINARY ☐

WAVELENGTH 20 - 200 μ

TEMPERATURE 100, 300 °K

METHOD Reflection

REFERENCE Manabe, et al. (36435)

REMARKS n-type material, indium-doped, carrier concentration = 5.25×10^{17} cm^{-3} at 300°K, resistivity = 1.92×10^{-2} ohm-cm at 300°K.

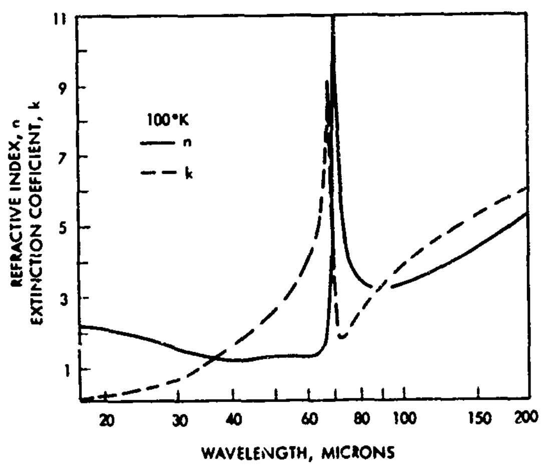


Figure 5-97

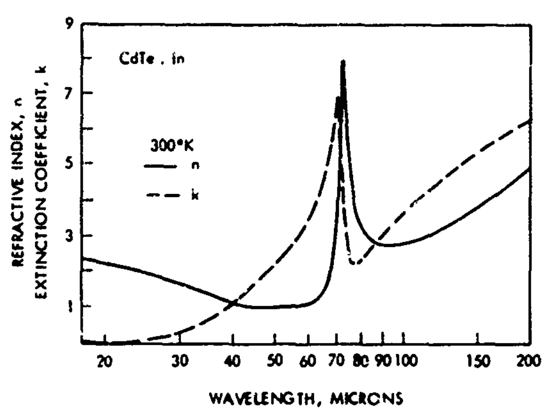
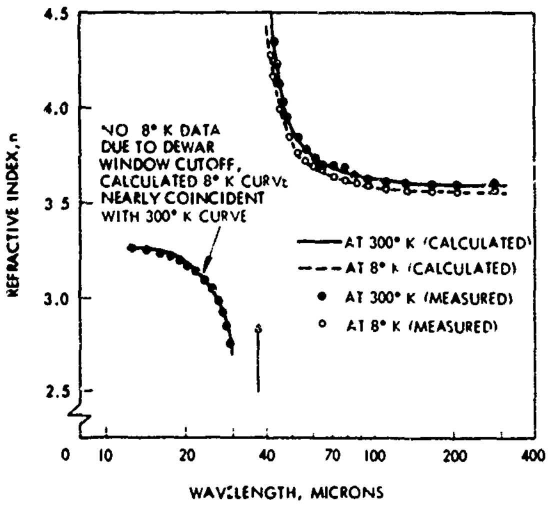


Figure 5-98

PARAMETER: Temperature

MATERIAL: Cadmium Telluride



FORM Bulk

THICKNESS 0.172 mm

RAY ORDINARY ☒, EXTRAORDINARY ☐

WAVELENGTH 12.5 - 300 μ

TEMPERATURE 8, 300 °K

METHOD Interference

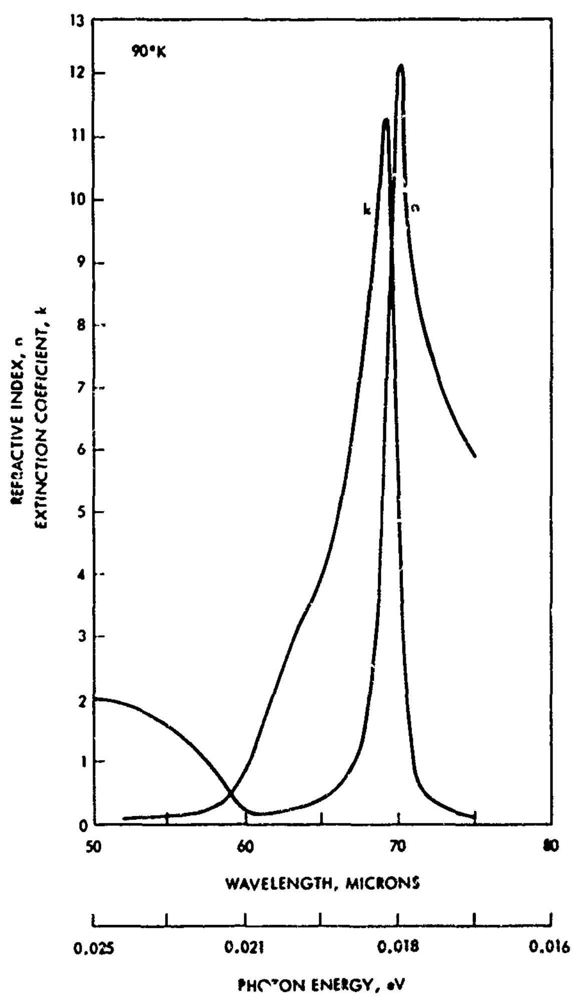
REFERENCE Johnson, et al. (40781)

REMARKS Resistivity = 8.5×10^5 ohm-cm

Figure 5-99

PARAMETER: Temperature

MATERIAL: Cadmium Telluride



FORM Bulk, Polycrystalline

THICKNESS Not stated mm

RAY ORDINARY ☒, EXTRAORDINARY ☐

WAVELENGTH 50 - 78 μ

TEMPERATURE 90, 300 °K

METHOD Reflection

REFERENCE Mitsuishi (481)

REMARKS

Figure 5-100

PARAMETER: Temperature (Cont'd from preceding page) **MATERIAL:** Cadmium Telluride

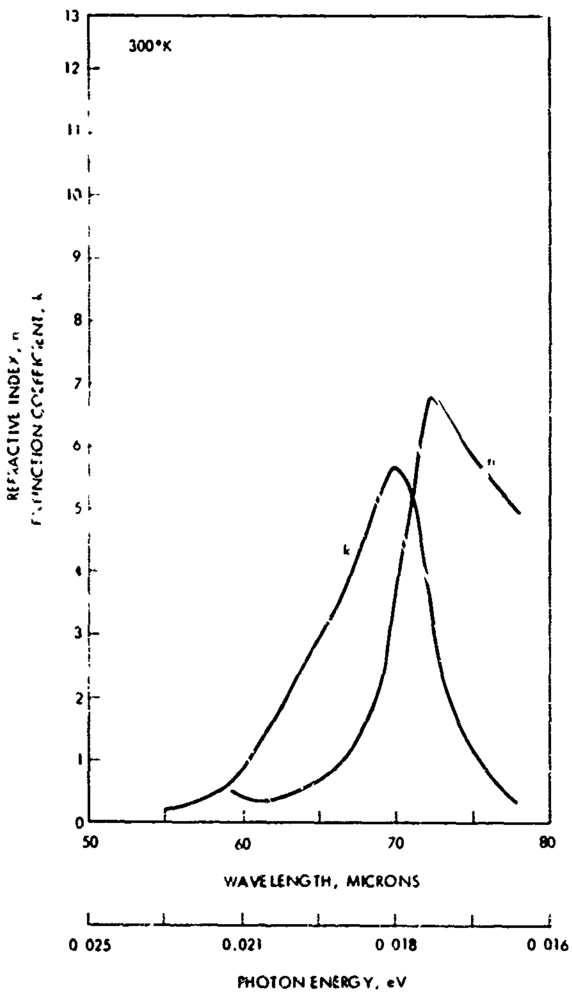


Figure 5-101

PARAMETER: Temperature

MATERIAL: Cadmium Telluride

FORM Bulk, Single Crystal

THICKNESS Not stated mm

RAY ORDINARY ☒, EXTRAORDINARY ☐

WAVELENGTH 10.6 μ

TEMPERATURE 293 - 318 °K

METHOD Interference

REFERENCE Weil & Johnson (41152)

REMARKS

Table 5-39

$$\boxed{(1/n)(dn/dT) = (4.02 \pm 0.05)\times 10^{-5}\ (^\circ K)^{-1}}$$

ZINC SELENIDE

INTRODUCTION

Zinc selenide is a semiconductor that has found application in infrared optics and in cathodoluminescence. Zinc selenide is a relatively new material and no generally recommended preparation method appears to have evolved thus far. Preparation methods include the direct preparation from the elements (Zn + Se) under argon and the reduction of a solution of zinc selenite hydrazine with subsequent decomposition of the precipitated hydrazine complex by addition of acetic acid. Typical crystal growth methods use zinc selenide powder as starting material for the growth of single crystals.

Zinc selenide transmits infrared light to a wavelength of eighteen microns as shown in Figure 1-9. Evaporated films of zinc selenide have a resistivity of 10^8 to 10^9 ohm-cm at 300^oK. The physical properties of zinc selenide were summarized in Table 1-1 and are given in greater detail in EPIC Report S-11.

DATA

All data presentations for zinc selenide are listed in Table 5-40 and a summary of wavelength and temperature coverage is plotted in Figure 5-102. Refractive index data as a function of wavelength are shown in Figures 5-103 to 5-111 and Tables 5-41 to 5-42. The data agree quite well with one another from one to twenty microns, but at longer wavelengths the data are rather scattered. The only single crystal result agrees fairly well with polycrystalline data over the range from 1.0 to 1.8 microns. The zinc selenide compilations also include a number of plots of extinction coefficient measurements. The temperature dependence of the refractive index and the extinction coefficient is the subject of Figures 5-112 to 5-118.

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Table 5-40. List of Zinc Selenide Data

Figure	Table	n or k	Form	Crystal	Wavelength, (Micron) From	To	Remarks	Parameter
5-103		n, k	Bulk	Single	20	85		Wavelength
5-104		n	Bulk	Polycryst	0.8	2.5		Wavelength
5-105		n	Bulk	Polycryst	2.0	13	198°K	Wavelength
5-106		n	Bulk	Polycryst	2.0	14	295°K	Wavelength
5-107	5-41	n	Bulk	Polycryst	1.0	29		Wavelength
5-108		n, k	Bulk	Polycryst	10	120	90°K	Wavelength
5-109		n, k	Bulk	Polycryst	10	125	300°K	Wavelength
5-110		n, k	Bulk	Polycryst	28	67	77, 290°K	Wavelength
5-111		n, k	Bulk	Polycryst	28	67	77, 290°K	Wavelength
	5-42	n	Film	*	0.8	1.9		Wavelength
5-112		n, k	Bulk	Single	20	85		Temperature
5-113		n	Bulk	Polycryst	2.0	13	198°K	Temperature
5-114		n	Bulk	Polycryst	2.0	14	295°K	Temperature
5-115		n, k	Bulk	Polycryst	10	120	90°K	Temperature
5-116		n, k	Bulk	Polycryst	10	125	300°K	Temperature
5-117		n, k	Bulk	Polycryst	28	67	77, 290°K	Temperature
5-118		n, k	Bulk	Polycryst	28	67	77, 290°K	Temperature

*Not stated

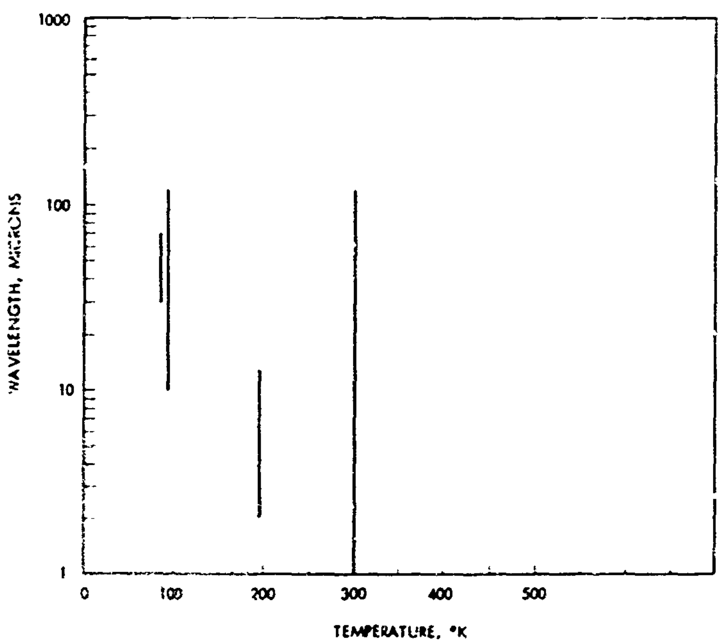
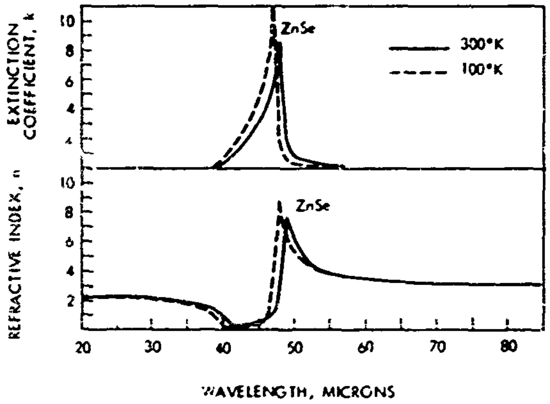


Figure 5-102. Wavelength and Temperature Range for Zinc Selenide Data

PARAMETER: Wavelength

MATERIAL: Zinc Selenide



FORM Bulk, Single Crystal

THICKNESS Not stated mm

RAY ORDINARY ☒ , EXTRAORDINARY ☐

WAVELENGTH 20 - 85 μ

TEMPERATURE 100, 300 °K

METHOD Reflection

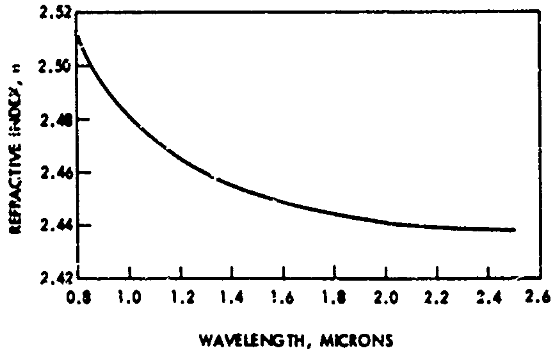
REFERENCE Manabe, et al. (28526)

REMARKS

Figure 5-103

PARAMETER: Wavelength

MATERIAL: Zinc Selenide



FORM Bulk, Polycrystalline

THICKNESS NA (Prism) mm

RAY ORDINARY ☒, EXTRAORDINARY ☐

WAVELENGTH 0.8 - 2.5 μ

TEMPERATURE ~298 °K

METHOD Deviation

REFERENCE Marple (15085)

REMARKS Crystal was prepared by bonding two to four single crystals together.

Figure 5-104

PARAMETER: Wavelength

MATERIAL: Zinc Selenide

FORM: Bulk, Polycrystalline

THICKNESS: NA (Wedge) mm

RAY: ORDINARY ☒ , EXTRAORDINARY ☐

WAVELENGTH: 2 - 14 μ

TEMPERATURE: 198, 295 °K

METHOD: Deviation

REFERENCE: Hilton and Jones [1967]

REMARKS:

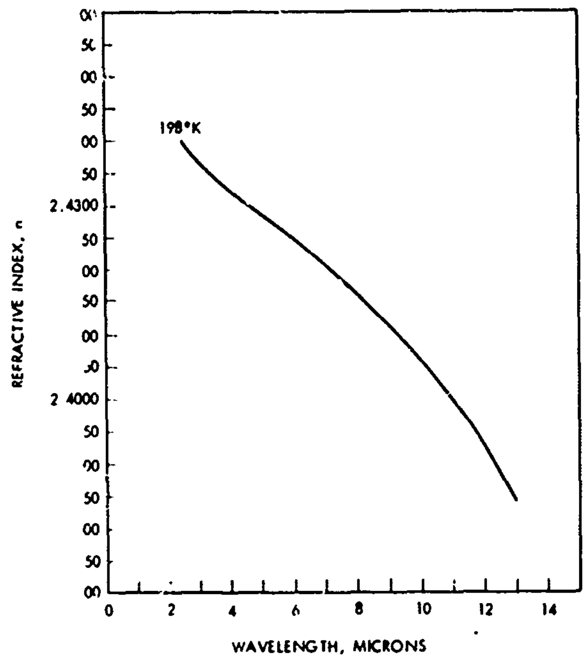


Figure 5-105

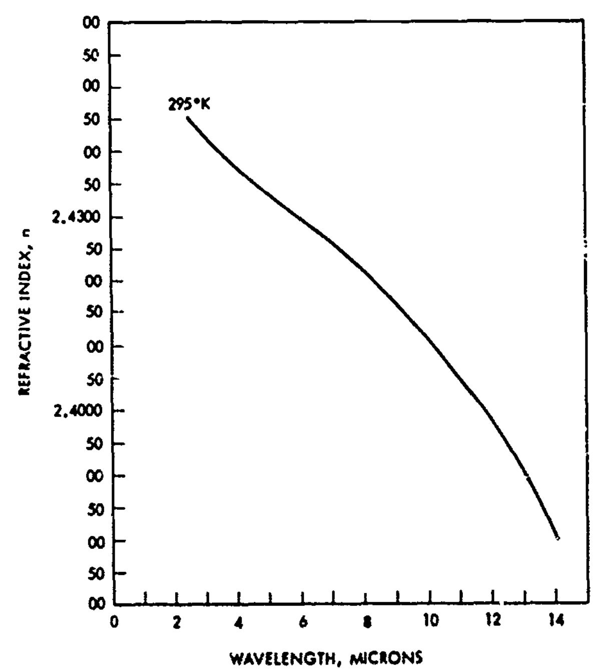
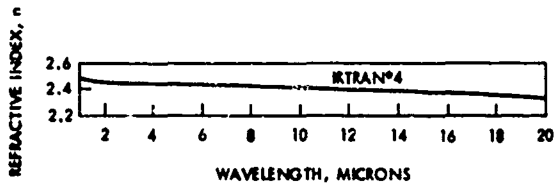


Figure 5-106

PARAMETER: Wavelength

MATERIAL: Zinc Selenide



FORM Bulk, Polycrystalline

THICKNESS Not stated mm

RAY ORDINARY ☒, EXTRAORDINARY ☐

WAVELENGTH 1.0 - 20 μ

TEMPERATURE 298 °K

METHOD Not stated

REFERENCE Kodak [1967]

REMARKS IRTRAN-4 material

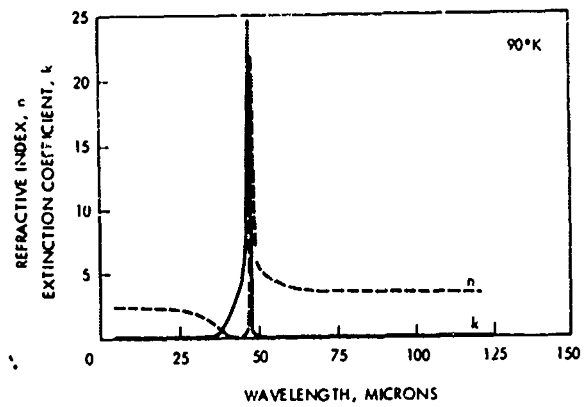
Figure 5-107

Wavelength, (Microns)	Refractive Index, n	Wavelength, (Microns)	Refractive Index, n
1.0000	2.485	7.0000	2.423
1.2500	2.466	7.2500	2.422
1.5000	2.456	7.5000	2.421
1.7500	2.450	7.7500	2.419
2.0000	2.447	8.0000	2.418
2.2500	2.444	8.2500	2.417
2.5000	2.442	8.5000	2.416
2.7500	2.441	8.7500	2.415
3.0000	2.440	9.0000	2.413
3.2500	2.438	9.2500	2.411
3.5000	2.437	9.5000	2.410
3.7500	2.436	9.7500	2.409
4.0000	2.435	10.0000	2.407
4.2500	2.434	11.0000	2.401
4.5000	2.433	12.0000	2.394
4.7500	2.433	13.0000	2.386
5.0000	2.432	14.0000	2.378
5.2500	2.431	15.0000	2.370
5.5000	2.430	16.0000	2.361
5.7500	2.429	17.0000	2.352
6.0000	2.428	18.0000	2.343
6.2500	2.426	19.0000	2.333
6.5000	2.425	20.0000	2.323
6.7500	2.424		

Table 5-41

PARAMETER: Wavelength

MATERIAL: Zinc Selenide



FORM Bulk, Polycrystalline

THICKNESS Not stated mm

RAY ORDINARY ☒ , EXTRAORDINARY ☐

WAVELENGTH 10 - 125 μ

TEMPERATURE 90, 300 °K

METHOD Reflection

REFERENCE Hadni, et al. (29510)

REMARKS

Figure 5-108

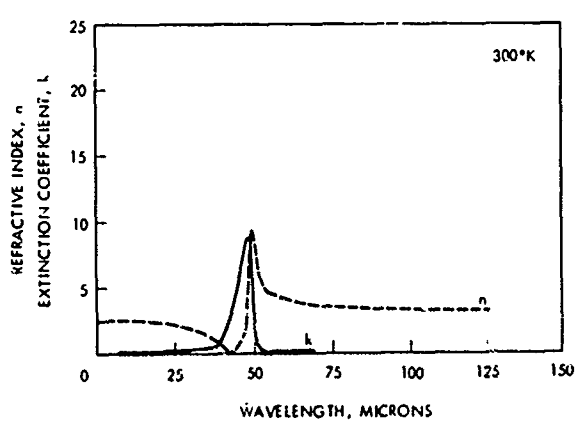


Figure 5-109

PARAMETER: Wavelength

MATERIAL: Zinc Selenide

FORM Bulk, Polycrystalline

THICKNESS Not stated mm

RAY ORDINARY ☒, EXTRAORDINARY ☐

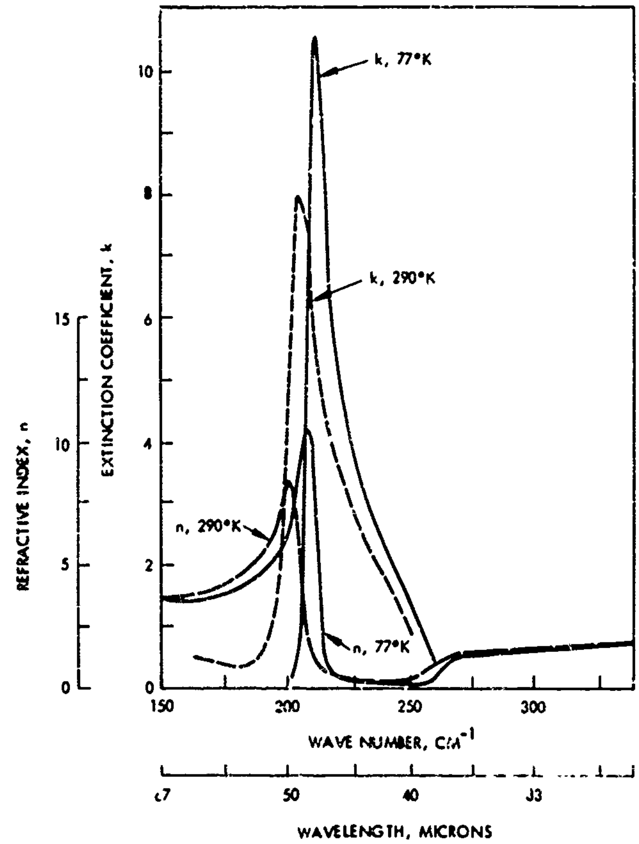
WAVELENGTH 28 - 67 μ

TEMPERATURE 77, 290 °K

METHOD Reflection

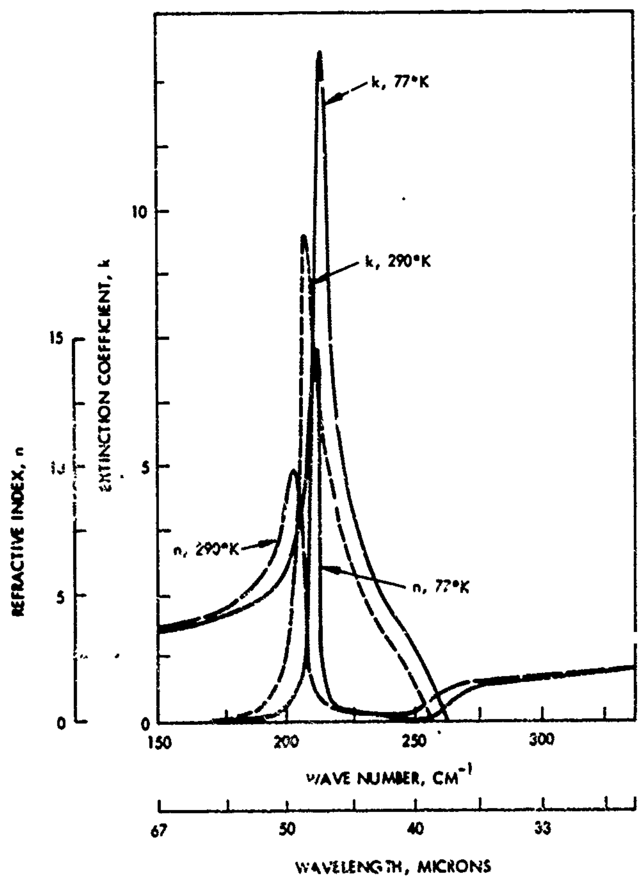
REFERENCE Hadni, et al. (34136)

REMARKS



Calculated by Kramers-Kronig Method

Figure 5-110



Calculated by Lorentz Oscillator Theory

Figure 5-111

PARAMETER: Wavelength

MATERIAL: Zinc Selenide

Wavelength, (Microns)	Refractive Index, n
0.8	2.50
0.9	2.47
1.0	2.46
1.1	2.45
1.2	2.44
1.3	2.43
1.5	2.42
1.7	2.41
>1.9	2.40

FORM Film

THICKNESS ~ 0.8×10^{-3} mm

RAY ORDINARY ☒, EXTRAORDINARY ☐

WAVELENGTH 0.8 - 1.9 μ

TEMPERATURE ~298 °K

METHOD Interference

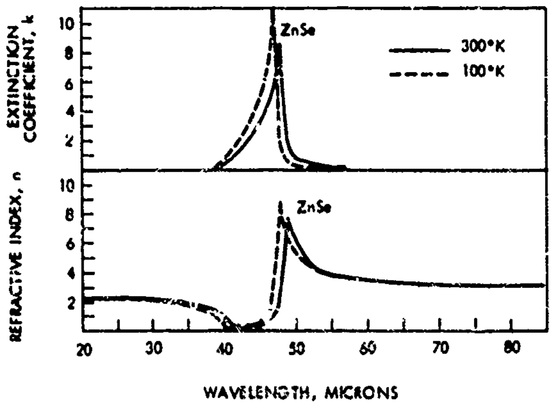
REFERENCE Fischer, et al. (15559)

REMARKS Evaporated film on borosilicate glass substrate.

Table 5-42

PARAMETER: Temperature

MATERIAL: Zinc Selenide



FORM Bulk, Single Crystal

THICKNESS Not stated mm

RAY ORDINARY ☒, EXTRAORDINARY ☐

WAVELENGTH 20 - 85 μ

TEMPERATURE 100, 300 °K

METHOD Reflection

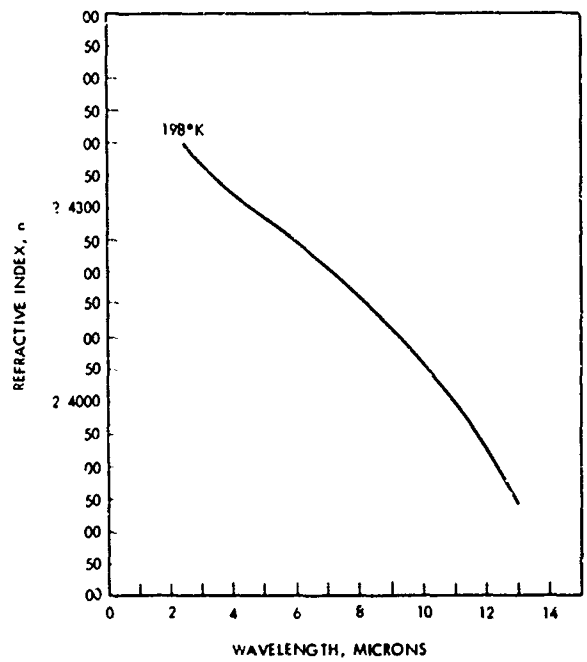
REFERENCE Manabe, et al. (28526)

REMARKS

Figure 5-112

PARAMETER: Temperature

MATERIAL: Zinc Selenide



FORM Bulk, Polycrystalline

THICKNESS NA (Wedge) mm

RAY ORDINARY ☒, EXTRAORDINARY ☐

WAVELENGTH 2 - 14 μ

TEMPERATURE 198, 295 °K

METHOD Deviation

REFERENCE Hilton and Jones [1967]

REMARKS

Figure 5-113

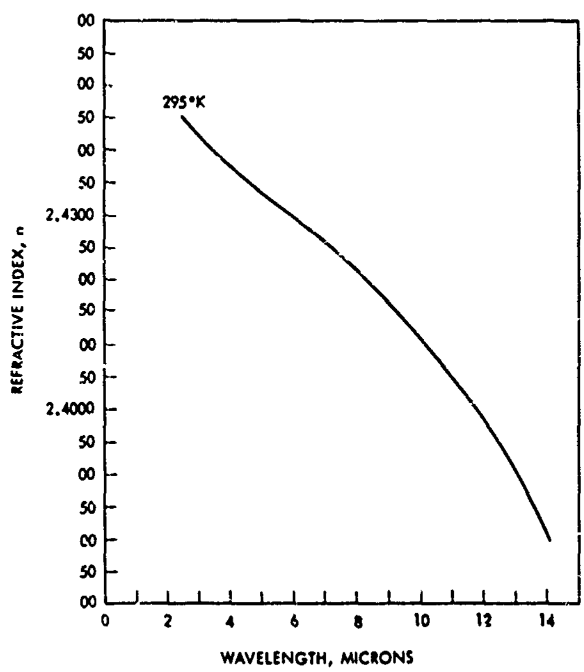


Figure 5-114

PARAMETER: Temperature

MATERIAL: Zinc Selenide

FORM Bulk, Polycrystalline

THICKNESS Not stated mm

RAY ORDINARY ☒, EXTRAORDINARY ☐

WAVELENGTH 10 - 125 μ

TEMPERATURE 90, 300 °K

METHOD Reflection

REFERENCE Hadni, et al. (29510)

REMARKS

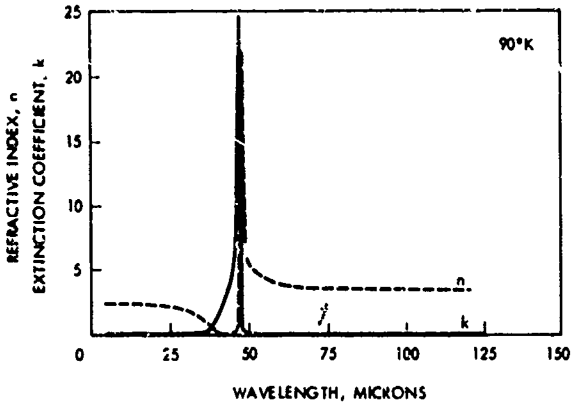


Figure 5-115

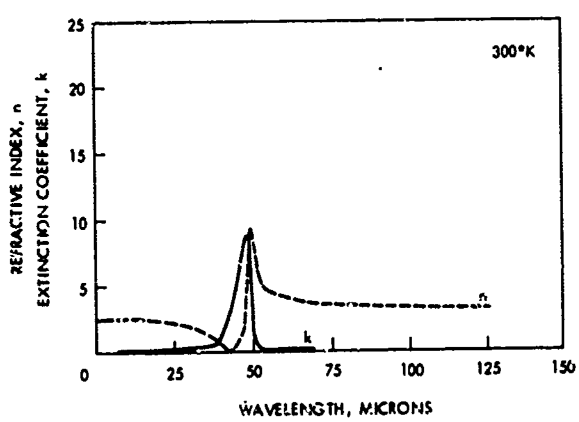
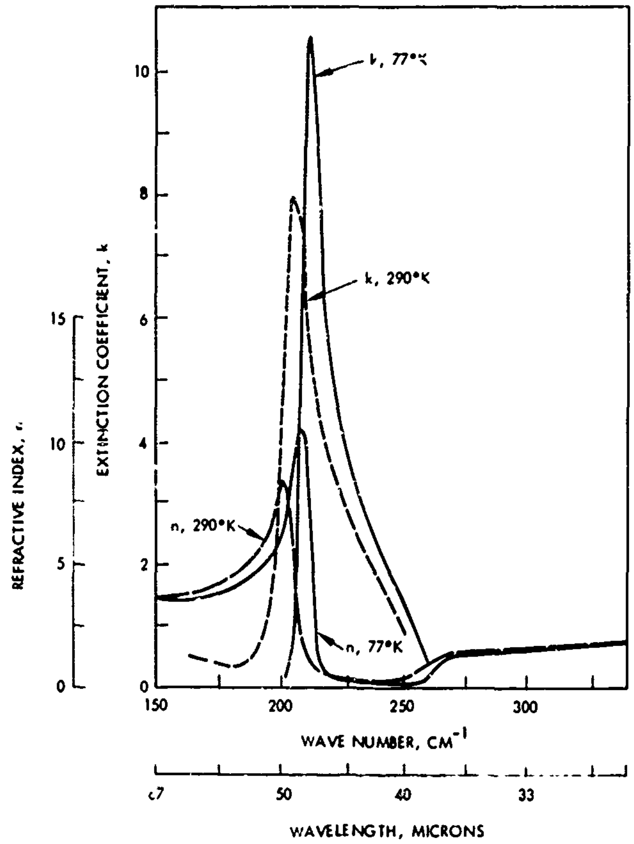


Figure 5-116

PARAMETER: Temperature

MATERIAL: Zinc Selenide



FORM Bulk, Polycrystalline

THICKNESS Not stated mm

RAY ORDINARY ☒, EXTRAORDINARY ☐

WAVELENGTH 28 - 67 μ

TEMPERATURE 77, 290 °K

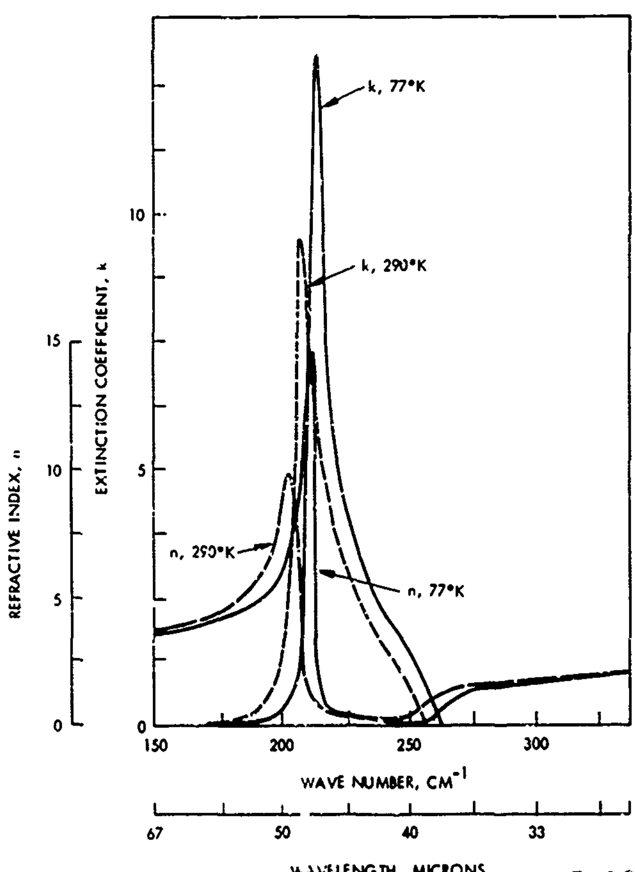
METHOD Reflection

REFERENCE Hadni, et al. (34136)

REMARKS ITRAN-4 material

Calculated by Kramers-Kronig method.

Figure 5-117



Calculated by Lorentz Oscillator Method

Figure 5-118

CHAPTER 6

REFRACTIVE INDEX DATA FOR SILICA-QUARTZ-SILICON DIOXIDE

GENERAL

This Chapter describes a class of materials called "quartz", "silica", or "silicon dioxide".

There exists in quartz and silica a great deal of confusion in nomenclature. Laufer [1965] distinguishes five materials which in turn are described by many terms. Table 6-1 presents Laufer's terms for the five materials.

Modern optical glasses are made under adequate quality control and many recent publications do not distinguish materials in the manner shown in Table 6-1. Therefore this Report distinguishes only two types of quartz or silica:

1. Crystalline Silica
2. Fused Silica

Table 6-1. Terms Used for Five Silica Materials

High Silica Glass	Natural Quartz	Cultured Quartz	Transparent Vitreous Silica	Translucent Fused Silica
Silica Glass	Quartz	Cultured Quartz	Quartz	Translucent Fused Quartz
Vitreous Silica	Crystalline Quartz	Synthetic Quartz	Quartz Glass	(Quarzgut, in German)
High Silica Glass	Quartz Crystal	Synthetic Quartz Crystal	(Quarzglas, in German)	Translucent Fused Silica
	Natural Quartz		Fused Quartz	Fused Silica
	Rock Crystal		Vitreous Quartz	Translucent Vitreous Silica
			Fused Quartz Glass	Vitreous Silica
			Optical Quartz Glass	
			Optical Fused Quartz	
			Clear Fused Quartz	
			Transparent Fused Quartz	
			Fused Silica	
			Synthetic Fused Silica	
			Transparent Fused Silica	
			Clear Fused Silica	
			Silica Glass	
			Transparent Vitreous Silica	
			Clear Vitreous Silica	
			Vitreous Silica	

SILICA, CRYSTALLINE

INTRODUCTION

Crystalline silica, also called α-quartz, is the only crystalline form of silica that is stable below 846°K at atmospheric pressure. It is a uniaxial birefringent crystal (hexagonal) that has a resistivity of approximately 10^{15} ohm-cm at 300°K. Crystalline silica exhibits strong optical absorption due to lattice absorption bands between 5 and 37 microns in wavelength, becoming transparent again from 50 to 1000 microns, as shown in Figure 1-4. The transmittance in the far infrared has led to the use of this material as window material in this region and for eliminating high-order radiation in far infrared grating spectrometers. Other applications of crystalline silica include piezoelectric crystals and electromechanical transducers.

Most high grade natural crystalline silica is obtained from Brasil. Material of similar quality has been synthesized by hydrothermal growing. The physical properties of crystalline silica are summarized in Table 1-1.

DATA

The data for crystalline silica are listed in Table 6-2 and detailed in Figures 6-1 to 6-15 and Tables 6-3 to 6-6. Table 6-3 represents a composite of early data for the near infrared region. The wavelengths covered in the data are from 1 to 600 microns and all data were gathered at room temperature. In additional to the refractive index for the ordinary ray, a great deal of refractive index data for the extraordinary ray is included. In general, the data show good agreement in refractive indices.

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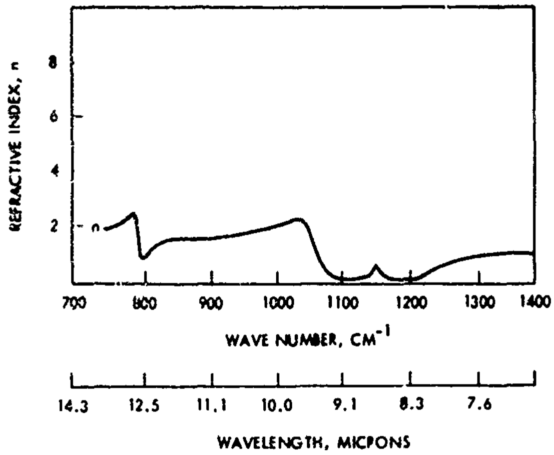
Table 6-2. List of Crystalline Silica Data

Figure	Table	n_o	n_e	Form	Crystal	Wavelength (Microns) From	Wavelength (Microns) To	Parameter
6-1		X		Bulk		7	14	Wavelength
6-2		X		Bulk		5	14	Wavelength
6-3		X		Bulk		6	33	Wavelength
6-4			X	Bulk		6	33	Wavelength
6-5		X	X	Bulk		6	35	Wavelength
	6-3	X	X	Bulk		1	4	Wavelength
6-6		X		Bulk		80	300	Wavelength
6-7			X	Bulk		80	300	Wavelength
6-8		X		Bulk		27	63	Wavelength
6-9			X	Bulk		27	63	Wavelength
6-10		X		Bulk		50	500	Wavelength
6-11			X	Bulk		50	500	Wavelength
6-12		X		Bulk		40	500	Wavelength
	6-4	X		Bulk		70	300	Wavelength
	6-5	X	X	Bulk		100	300	Wavelength
6-13		X		Bulk		180	600	Wavelength
6-14			X	Bulk		180	600	Wavelength
6-15		X		Bulk		180	500	Wavelength
	6-6	X		Bulk		337	337	Wavelength

PARAMETER: Wavelength

MATERIAL: Silica, Crystalline



FORM Bulk

THICKNESS not stated mm

RAY ORDINARY ☒, EXTRAORDINARY ☐

WAVELENGTH 7-14 μ

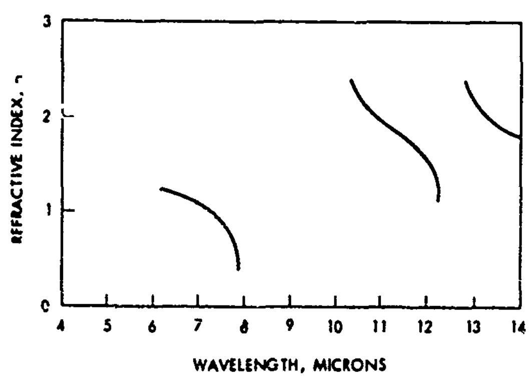
TEMPERATURE ~298 °K

METHOD Reflection

REFERENCE Simon (39827)

REMARKS Crystal cut perpendicular to the optical axis

Figure 6-1



THICKNESS 0.025 - 0.05 mm

RAY ORDINARY ☒, EXTRAORDINARY ☐

WAVELENGTH 5-14 μ

TEMPERATURE ~298 °K

METHOD Interference

REFERENCE Ramadier-Delbès (39712)

REMARKS

Figure 6-2

PARAMETER: Wavelength

MATERIAL: Silica, Crystalline

FORM Bulk

THICKNESS 0.030 mm

RAY ORDINARY ☒, EXTRAORDINARY ☐

WAVELENGTH 6-33 μ

TEMPERATURE 298 °K

METHOD Reflection

REFERENCE Haefele (40240)

REMARKS

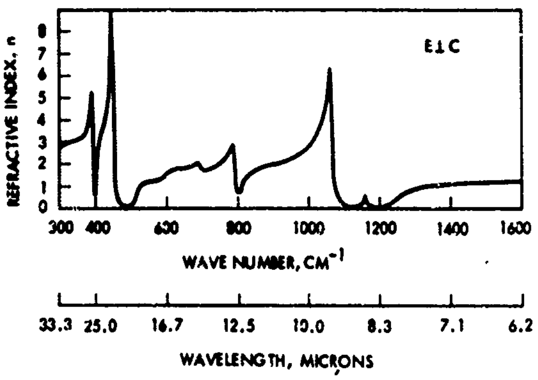


Figure 6-3

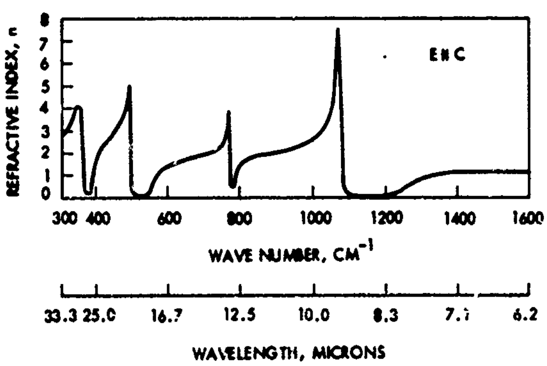
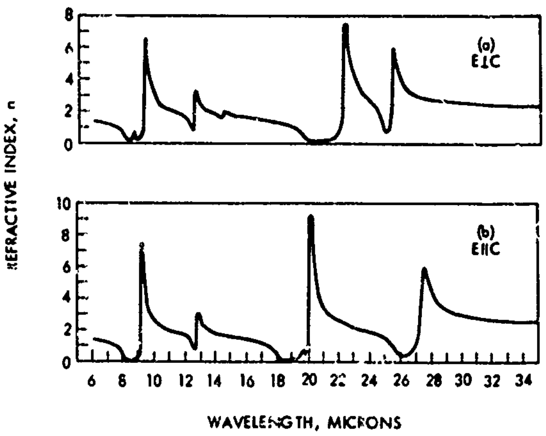


Figure 6-4

PARAMETER: Wavelength

MATERIAL: Silica, Crystalline



THE REFRACTIVE INDEX OF QUARTZ FOR THE ORDINARY RAY (a) AND THE EXTRAORDINARY RAY (b) AS OBTAINED FROM THE DISPERSION ANALYSIS OF THE REFLECTIVITY.

FORM Bulk

THICKNESS 0.0262 mm

RAY ORDINARY ☒ , EXTRAORDINARY ☒

WAVELENGTH 6-35 μ

TEMPERATURE 297 °K

METHOD Reflectivity

REFERENCE Spitzer & Kleinman (1860)

REMARKS α-quartz

Figure 6-5

Wavelength, (Microns)	Refractive Index		Ref
	n_o	n_o	
1.0417	1.53442	1.54317	a
1.0973	1.53366	1.54238	a
1.1592	1.53283	1.54152	a
1.2288	1.53192	1.54057	a
1.3070	1.53090	1.53951	a
1.3685	1.53011	1.53860	a
1.3958	1.52977	1.53632	a
1.4792	1.52865	1.53716	a
1.5414	1.52781	1.53630	a
1.6146	1.52679	1.53524	a
1.6815	1.52583	1.53422	a
1.7437	1.5248	1.53319	a
1.9457	1.52184	1.53004	a
2.0531	1.52005	1.52823	a
2.60	1.50966	–	b
3.00	1.49953	–	b
3.50	1.48451	–	b
4.00	1.46617	–	b
4.20	1.4569	–	c

THICKNESS Not stated mm

RAY ORDINARY ☐ , EXTRAORDINARY ☒

WAVELENGTH 1.0 – 4.2 μ

TEMPERATURE 291 °K

METHOD Not stated

REFERENCE Smakula [1952]

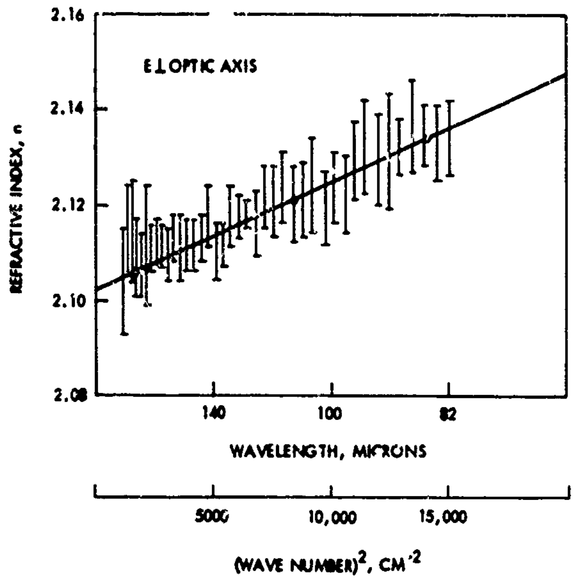
REMARKS References for this Table:

(a) Carvallo, A., Compt. rend. Vol. 126, (1898), p. 728.
(b) Kohlrausch, F., "Praktische Physik," Vol. II, 18th Ed., B.G. Teubner, Leipzig, (1943), p. 528.
(c) Rubens, H., Wied. Ann., Vol. 54, (1895), p. 488.

Table 6-3

PARAMETER: Wavelength

MATERIAL: Silica, Crystalline



FORM Bulk

THICKNESS ~1 mm

RAY ORDINARY ☒, EXTRAORDINARY ☐

WAVELENGTH 80 – 300 μ

TEMPERATURE 298 °K

METHOD Transmission

REFERENCE Roberts & Coon (18253)

REMARKS Brazilian Quartz

Figure 6-6

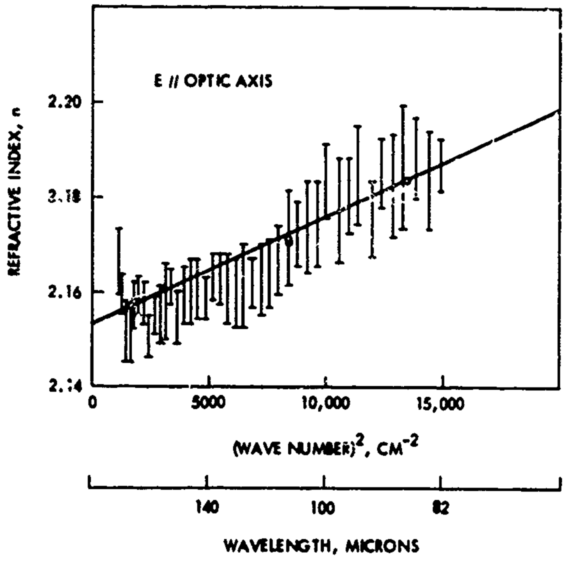


Figure 6-7

PARAMETER: Wavelength

MATERIAL: Silica, Crystalline

FORM Bulk

THICKNESS 0.0766 mm

RAY ORDINARY ☒ , EXTRAORDINARY ☒

WAVELENGTH 27 – 63 μ

TEMPERATURE 301 °K

METHOD Interference

REFERENCE Russell & Bell (28888)

REMARKS

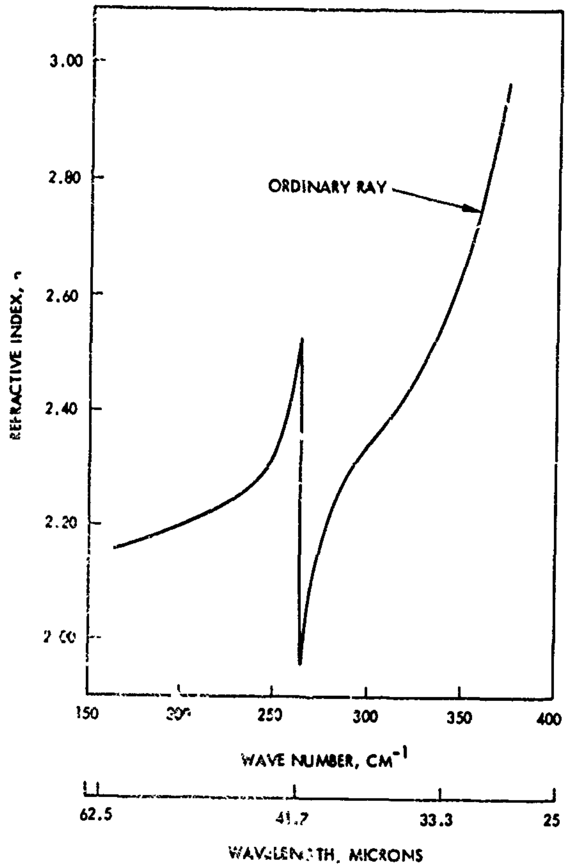


Figure 6-8

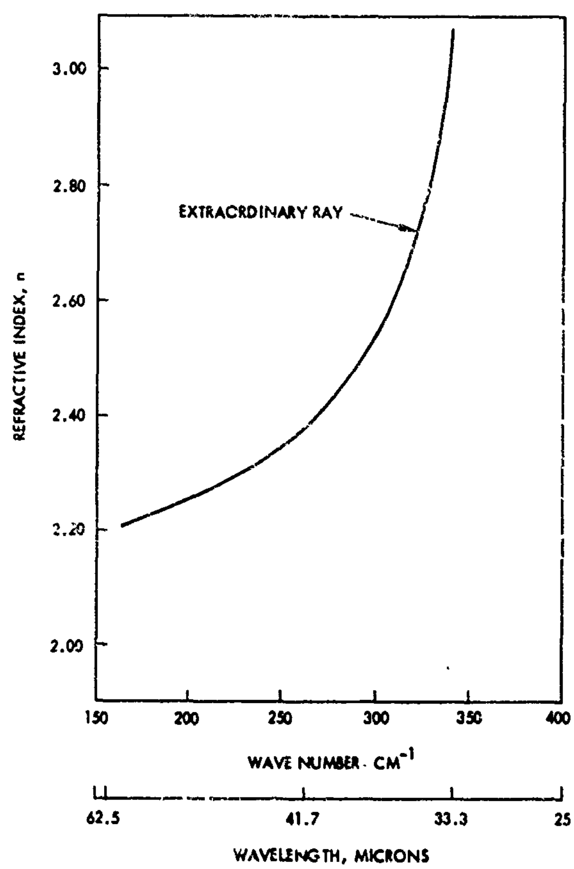


Figure 6-9

PARAMETER: Wavelength

MATERIAL: Silica, Crystalline

FORM Bulk

THICKNESS 0.255 mm

RAY ORDINARY ☒ EXTRAORDINARY ☒

WAVELENGTH 100 – 300 μ

TEMPERATURE 300 °K

METHOD Interference

REFERENCE Berman & Zhukov (36032)

REMARKS

(a) crystal cut ⊥ to optical axis

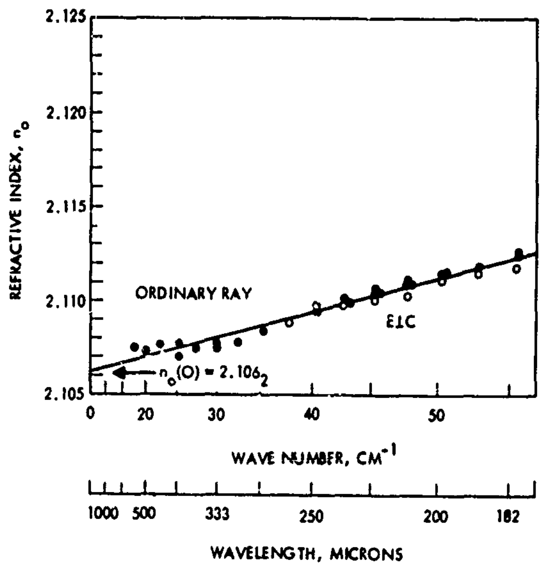
(b) crystal cut ∥ to optical axis, (X cut)

Wavelength, Microns	Refractive Index, Ordinary Ray (n_o)	Refractive Index, Extraordinary Ray (n_e)
100-300	2.10 ± 0.03 (a)	–
165-240	2.11 ± 0.03 (b)	2.16 ± 0.02 (b)

Table 6-5

PARAMETER: Wavelength

MATERIAL: Silica, Crystalline



Determination of the extrapolated, zero-frequency ordinary- and extraordinary-ray refractive indices of quartz. The extrapolated values, $n_o(0) = 2.1062$ and $n_e(0) = 2.1538$, have an experimental uncertainty of ±0.001, which is much larger than is apparent from the consistency of the data

FORM	Bulk
THICKNESS	1.0497, 4.7873 mm
RAY	ORDINARY ☒, EXTRAORDINARY ☒
WAVELENGTH	180 – 600 μ
TEMPERATURE	301 °K
METHOD	Interference
REFERENCE	Russell & Bell (28888)
REMARKS	

Figure 6-13

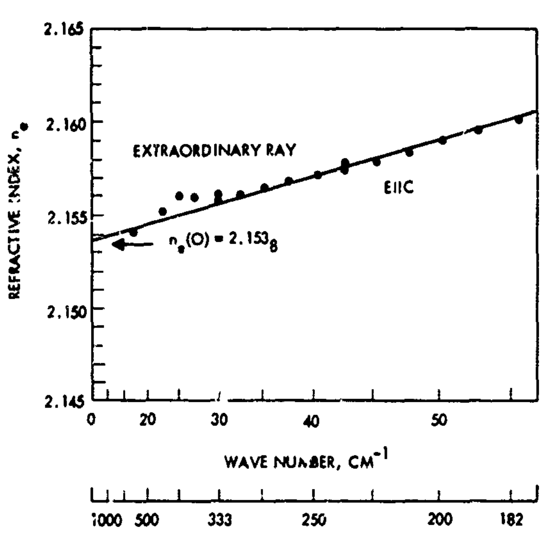
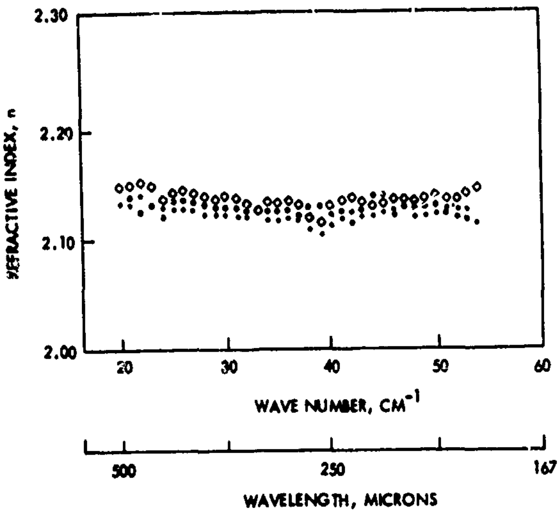


Figure 6-14

PARAMETER: Wavelength

MATERIAL: Silica Crystalline



FORM Bulk

THICKNESS 0.48 mm

RAY ORDINARY ☒, EXTRAORDINARY ☐

WAVELENGTH 180 – 500 μ

TEMPERATURE ~298 °K

METHOD Interference

REFERENCE Chamberlain (40179)

REMARKS ◇run 1; ○run 2; ● run 3

Figure 6-15

Wavelength, Microns	Refractive Index, n
337	2.132 ± 0.026

THICKNESS 3-7 mm

RAY ORDINARY ☒, EXTRAORDINARY ☐

WAVELENGTH 337 μ

TEMPERATURE ~298 °K

METHOD Interference

REFERENCE Chamberlain & Gebbie(40177)

REMARKS Use of CN maser as radiation source.

Table 6-6

PARAMETER: Wavelength

MATERIAL: Silica, Crystalline

FORM Bulk

THICKNESS 1.0497, 4.7873 mm

RAY ORDINARY ☒, EXTRAORDINARY ☒

WAVELENGTH 50 — 500 μ

TEMPERATURE 301 °K

METHOD Interference

REFERENCE Russell & Bell (28888)

REMARKS

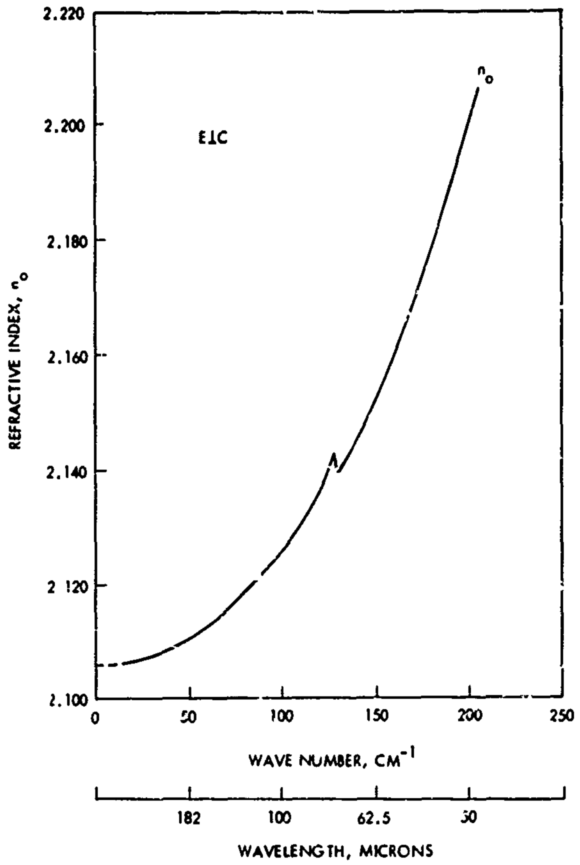


Figure 6-10

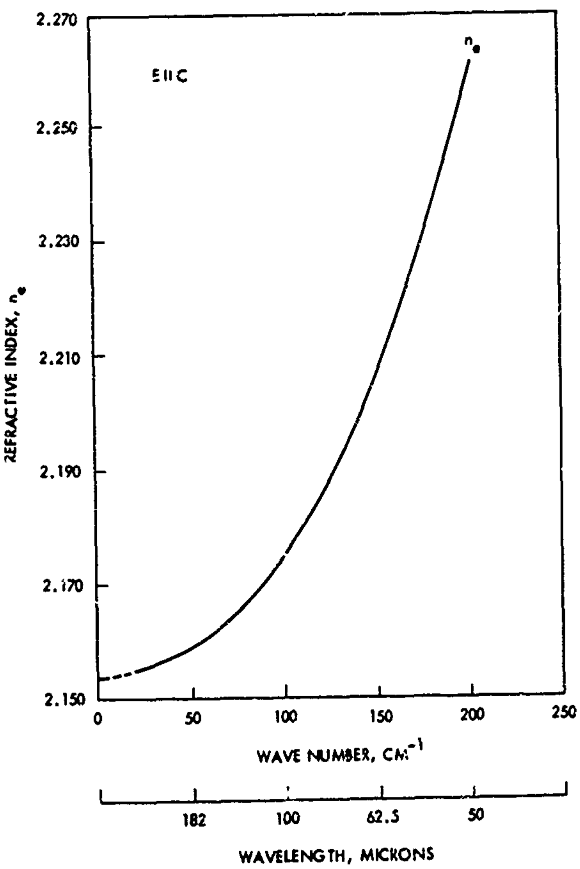
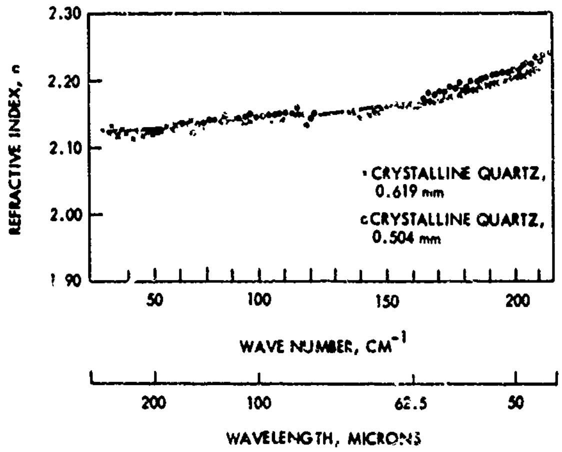


Figure 6-11

PARAMETER: Wavelength

MATERIAL: Silica Crystalline



FORM Bulk

THICKNESS ~0.6 mm

RAY ORDINARY ☒, EXTRAORDINARY ☐

WAVELENGTH 40 – 500 μ

TEMPERATURE ~298 °K

METHOD Interference

REFERENCE Geick (39706)

REMARKS

Figure 6-12

Wavelength, (Microns)	Refractive Index, n
70-300	2.2 ± 0.02

THICKNESS 1, 2 mm

RAY ORDINARY ☒, EXTRAORDINARY ☐

WAVELENGTH 70 – 300 μ

TEMPERATURE 298 °K

METHOD Interference

REFERENCE Poinsot, et al., (40710)

REMARKS

Table 6-4

SILICA, FUSED

INTRODUCTION

Fused silica is considered to be a glass and in common with other glasses, its transmission spectrum shows a deep absorption near 2.8 microns and poor transmission at longer wavelengths (Figure 1-5). The absorption in this region is caused by O-H stretching bands. Fused silica is used in innumerable technical applications because of its optical, thermal, mechanical and electrical properties.

Classically, fused silica is prepared by fusion of crystalline silica. Material of very high pruity can be made by hydrolysis of silicon tetrachloride at high temperature where the product, (fused silica) is deposited on a substrate.

The physical properties of fused silica are summarized in Table 1-1 and its transmission in the far infrared is plotted in Figure 1-6.

DATA

The data for fused silica are listed in Table 6-7 and their temperature range is plotted in Figure 6-16. Refractive index spectra for bulk fused silica are offered in Figures 6-17 to 6-23 and Tables 6-8 to 6-15; similar data for film fused silica are provided in Figures 6-24 and 6-25. Comparison of the data shows good agreement to approximately eight microns with a wider spread in data at longer wavelengths. The meager film data show good agreement with bulk data. The temperature dependence of the refractive index of bulk fused silica is the subject of Table 6-16 and Figure 6-26, while film data are shown in Figure 6-27. Figure 6-27 indicates an increase in refractive index with temperature at wavelengths below nine microns, and the opposite effect at longer wavelengths. The effects of ultraviolet radiation or simulated Apollo mission space environment are the subjects of Figure 6-28 and Table 6-17, respectively.

Table 6-7. List of Fused Silica Data

Figure	Table	n, k	Form	Crystal	Wavelength (microns) From	To	Remarks	Parameter
6-17		n	Bulk		0.4	3.5		Wavelength
6-18		n	Bulk		0.2	3.5		Wavelength
	6-8	n	Bulk		0.7	3.7		Wavelength
	6-9	n	Bulk		0.4	1.08		Wavelength
	6-10	n	Bulk		0.7	3.7		Wavelength
	6-11	n	Bulk		1.0	1.5		Wavelength
	6-12	n	Bulk		1.0	3.4		Wavelength
	6-13	n	Bulk		1.0	2.6		Wavelength
6-19		n	Bulk		7.7	12		Wavelength
6-20		n	Not Stated		6	100		Wavelength
6-21		n	Not Stated		30	2000		Wavelength
	6-14	n	Bulk		50	400		Wavelength
6-22		n	Bulk		85	200		Wavelength
6-23		n	Bulk		111	600		Wavelength
	6-15	n, k	Bulk		2000	2000		Wavelength
6-24		n	Film		0.2	1.6		Wavelength
6-25		n	Film		7	11	291-1543°K	Wavelength
	6-16	n	Bulk		1.0	3.4	299-1101°K	Temperature
6-26		dn/dT	Bulk		0.2	4.0	293-303	Temperature
6-27		n	Film		7	11	291-1543	Temperature
6-28		n	Film		0.2	1.5	UV Light	Radiation
	6-17	n	Bulk		0.23	3.4	Space Radiation	Radiation

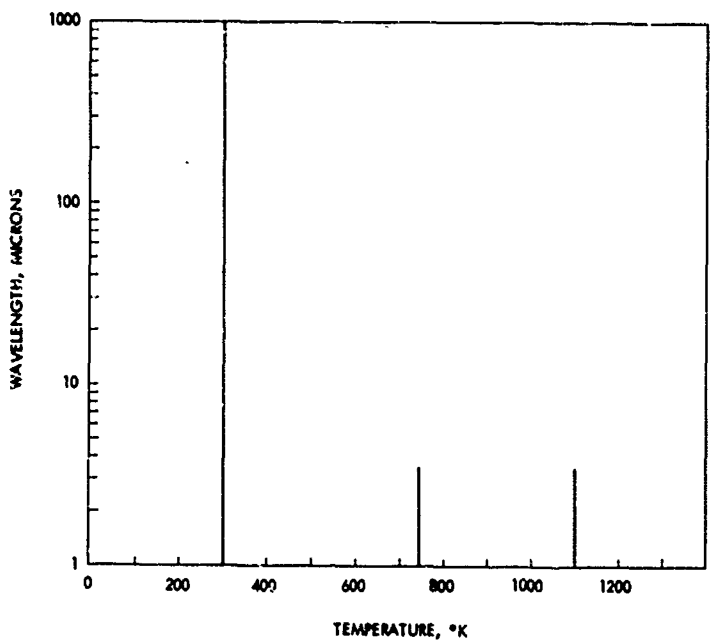
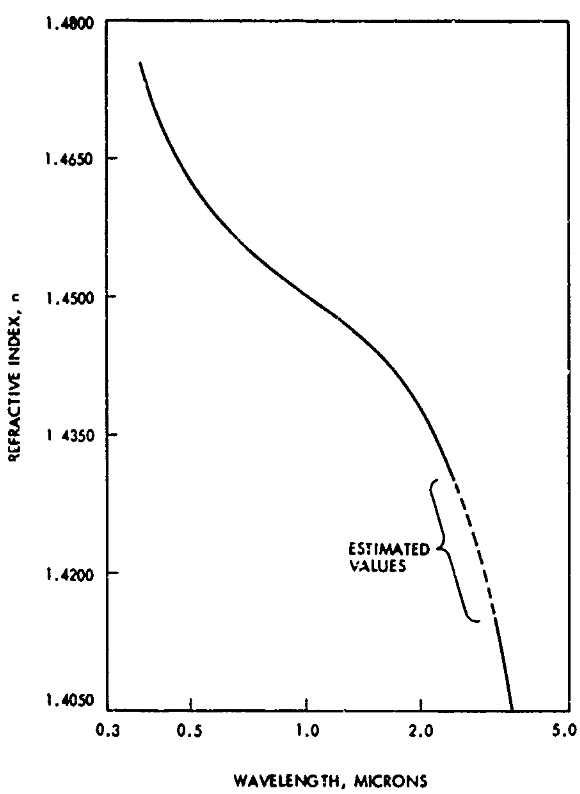


Figure 6-16. Wavelength and Temperature Range of Fused Silica Data

PARAMETER: Wavelength

MATERIAL: Silica, Fused



FORM Bulk

THICKNESS NA (Prism) mm

RAY ORDINARY ☒, EXTRAORDINARY ☐

WAVELENGTH 0.4 - 3.5 μ

TEMPERATURE 297 °K

METHOD Deviation

REFERENCE Rodney and Spindler (39714)

REMARKS Heraeus B quartz

Most probable values of refractive indices of pure fused-quartz at 297°K for various wavelengths, computed from equation (1)

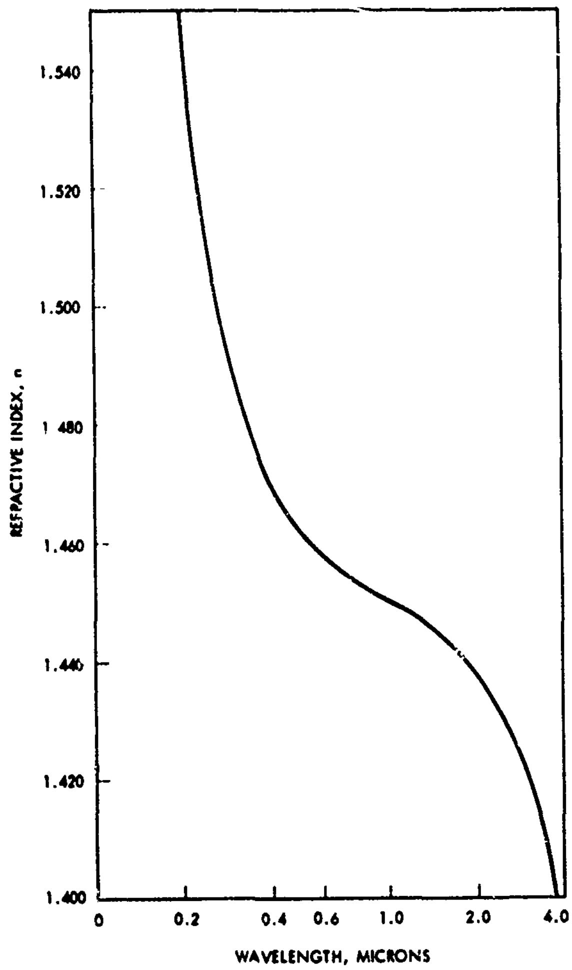
Figure 6-17

Equation (1) $$n^2 = 2.979864 + \frac{0.008777808}{\lambda^2 - 0.010609} - \frac{84.06224}{96.00000 - \lambda^2}$$

where λ = wavelength in microns.

PARAMETER: Wavelength

MATERIAL: Silica, Fused



FORM Bulk

THICKNESS NA (Prism) mm

RAY ORDINARY ☒ , EXTRAORDINARY ☐

WAVELENGTH 0.2 - 3.5 μ

TEMPERATURE 293 °K

METHOD Deviation

REFERENCE Malitson (21758)

REMARKS The dispersion equation (2) is valid for interpolation to five decimal places over the measured wavelength range.

Figure 6-18

Equation (2)
$$n^2 - 1 = \frac{0.6961663\lambda^2}{\lambda^2 - (0.0684043)^2} + \frac{0.4079426\lambda^2}{\lambda^2 - (0.1162414)^2} + \frac{0.8974794\lambda^2}{\lambda^2 - (9.896161)^2},$$

where λ = wavelength in microns.

PARAMETER: Wavelength

MATERIAL: Silica, Fused

FORM Bulk

THICKNESS NA (Prism) mm

RAY ORDINARY ☒ EXTRAORDINARY ☐

WAVELENGTH 0.7 - 3.7 μ

TEMPERATURE 293 °K

METHOD Deviation

REFERENCE Malitson (21758)

REMARKS Computed refractive index for three products

Table 6-8. Computed Refractive Index and Residuals

Wavelength microns	Spectral source	Computed index	C-D-G-E[a] residual X 10^6	Corning No. 7940 residual X 10^6	Dynasil residual X 10^6	General Electric No. 151 residual X 10^6
0.706519	He	1.455145	+ 5	+ 10	+ 12	+ 7
0.852111	Cs	1.452465	+ 5	+ 8	+ 3	+ 5
0.894350	Cs	1.451835	+ 5	+ 11	+ 5	+ 10
1.01398	Hg	1.450242	+ 8	+ 6	+ 3	+ 6
1.08297	He	1.449405	- 5	+ 8	+ 1	+ 9
1.12866	Hg	1.448869	+ 1	+ 7	+ 8	+ 9
1.3622	Hg	1.446212	- 12	- 6	- 14	- 12
1.39506	Hg	1.445836	+ 4	- 1	+ 4	- 3
1.4695	Cs	1.444975	- 5	+ 3	+ 9	+ 10
1.52952	Hg	1.444268	+ 2	+ 8	+ 6	0
1.6606	TCB[b]	1.442670	- 20	- 14	- 19	- 11
1.681	Poly[c]	1.442414	+ 6	- 2	- 10	+ 8
1.6932	Hg	1.442260	0	+ 7	- 6	+ 1
1.70915	Hg	1.442057	+ 3	0	+ 3	- 1
1.81307	Hg	1.440699	+ 21	- 7	- 7	+ 6
1.97009	Hg	1.438519	+ 1	+ 6	+ 12	+ 12
2.0581	He	1.437224	4	- 3	- 9	- 11
2.1526	TCB	1.435769	- 29	- 22	- 25	- 24
2.32542	Hg	1.432928	- 18	- 10	- 3	- 6
2.4374	TCB	1.430954	- 24	- 23	- 21	- 14
3.2439	Poly	1.413118	+ 32	+ 21	+ 29	+ 25
3.2668	Poly	1.412505	+ 25	+ 20	+ 30	+ 25
3.3026	Poly	1.411535	+ 25	+ 32	+ 30	+ 28
3.422	Poly	1.408180	+ 20	+ 40	+ 42	+ 37
3.5070	Poly	1.405676	- 16	- 26	- 20	- 10
3.5564	TCB	1.404174	- 24	- 27	- 29	- 18
3.7067	TCB	1.399389	- 19	- 22	- 14	- 9
Average of absolute values of residuals			10.5	11.9	12.2	11.7

a Residuals for arithmetical-mean table of values compiled from experimental data of Corning (C), Dynasil (D), and General Electric (G. E.).
b TCB = 1, 2, 4 - Trichlorobenzene.
c Poly = Polystyrene.

Table 6-9

Intracompany Comparison of Refractive Index Variation

Wavelength, (Microns)	Product											
	Corning No. 7940 residual X 10^6				Dynasil residual X 10^6				General Electric No. 151 residual X 10^6			
	1	2	3	4	1	2	3	4	1	2	3	4
0.4047	11	26	24	20	4	27	21	21	11	12	-12	14
0.4861	16	27	16	21	5	29	19	21	7	15	- 7	12
0.5461	14	24	22	17	5	35	25	16	11	12	-13	12
0.5893	12	27	23	27	0	18	20	22	12	13	- 8	12
0.6563	12	23	19	19	1	27	22	23	13	10	- 7	14
0.7065	17	28	20	18	2	31	23	23	13	15	-11	17
0.8944	11	26	22	19	3	31	19	25	11	12	- 8	13
1.014	16	21	20	20	6	30	26	22	14	13	-11	14
1.083	15	24	25	25	7	35	25	25	13	16	- 9	12
Av. Δn	13.5	24.9	20.0	21.6	3.5	27.4	20.4	20.5	11.3	12.9	- 9.6	13.2

NOTE: Numbered columns under each brand indicate individual specimens. The residuals are differences in the sixth decimal place of index between measured values and those computed by dispersion Equation (2). Each n is an average for the 18 wavelengths which were used. (See Figure 6-18 for Equation (2).

PARAMETER: Wavelength

MATERIAL: Silica, Fused

		Refractive Index			
Wavelength, (Microns)	Spectral Source	Four-term Fit to 180 Data Points Computed	Corning	Dynasil	G. E.
0.706519	He	1.455154	+ 1	+ 3	- 2
0.852111	Cs	1.452475	- 2	- 7	- 5
0.894350	Cs	1.451845	+ 2	- 4	+ 1
1.01398	Hg	1.450250	- 2	- 5	- 2
1.08297	He	1.449412	+ 1	- 6	+ 7
1.12866	Hg	1.448875	+ 1	+ 2	+ 3
1.3622	Hg	1.446213	- 7	- 15	- 13
1.39506	Hg	1.445837	- 2	+ 3	- 4
1.4695	Cs	1.444974	+ 4	+ 10	+ 11
1.52952	Hg	1.444266	+ 10	+ 8	+ 2
1.6606	TCB[a]	1.442666	- 10	- 15	- 7
1.681	Poly[b]	1.442409	+ 3	- 5	+ 13
1.6932	Hg	1.442255	+ 12	- 1	+ 6
1.70913	Hg	1.442052	+ 5	+ 8	+ 4
1.81307	Hg	1.440692	- 0	- 0	+ 13
1.97009	Hg	1.438512	+ 14	+ 20	+ 20
2.0581	He	1.437216	+ 5	- 1	- 3
2.1526	TCB	1.435762	- 15	- 18	- 17
2.32542	Hg	1.432922	- 4	+ 3	- 0
2.4374	TCB	1.430951	- 20	- 18	- 11
3.2439	Poly	1.413138	+ 1	+ 9	+ 5
3.2668	Poly	1.412525	- 0	+ 10	+ 5
3.3026	Poly	1.411554	+ 13	+ 11	+ 9
3.422	Poly	1.408194	+ 26	+ 28	+ 23
3.5070	Poly	1.405683	- 13	- 27	- 17
3.5564	TCB	1.404175	- 28	- 30	- 19
3.7067	TCB	1.399360	+ 7	+ 15	+ 20

a TCB = 1, 2, 4 - Trichlorobenzene.
b Poly = Polystyrene.

FORM Bulk

THICKNESS NA (Prism) mm

RAY ORDINARY ☒, EXTRAORDINARY ☐

WAVELENGTH 0.7 - 3.7 μ

TEMPERATURE 293 °K

METHOD Deviation

REFERENCE Brixner (29206)

REMARKS Computations based on data from Malitson (21758), giving average deviation of 4.3×10^{-6}.

Table 6-10

Wavelength, (Microns)	Refractive Index, n
1.01398	1.45044
1.12866	1.44906
1.36728	1.44650
1.39506	1.44607
1.52952	1.44450

THICKNESS NA (Prism) mm

RAY ORDINARY ☒, EXTRAORDINARY ☐

WAVELENGTH 1.0 - 1.5 μ

TEMPERATURE 298 °K

METHOD Deviation

REFERENCE Zernike (39697)

REMARKS Measurement on GE-101 silica, performed in air.

Table 6-11

PARAMETER: Wavelength

MATERIAL: Silica, Fused

Refractive Index

Wavelength (Microns)	Refractive Index, n 299°K	744°K	1101°K
1.01398	1.45039	1.45562	1.45960
1.12866	1.44903	1.45426	1.45820
1.254*	1.44772	1.45283	1.45700
1.36728	1.44635	1.45140	1.45549
1.470*	1.44524	1.45031	1.45440
1.52452	1.44444	1.44961	1.45352
1.660*	1.44307	1.44799	1.45174
1.701	1.44230	1.44733	1.45140
1.981*	1.43863	1.44361	1.44734
2.262*	1.43430	1.43933	1.44306
2.553*	1.42949	1.43450	1.43854
3.00*	1.41995	1.42495	1.42877
3.245*	1.41353	1.41893	1.42243
3.37*	1.40990	1.41501	1.41915

$\delta n = 23 \times 10^{-5}$ (experimental error)

*Wavelength determination by narrow band interference filter.

FORM Bulk

THICKNESS NA (Prism) mm

RAY ORDINARY ☒, EXTRAORDINARY ☐

WAVELENGTH 1.0 - 3.4 μ

TEMPERATURE 299 - 1101 °K

METHOD Deviation

REFERENCE Neu, et al. (40260)

REMARKS Corning Code 7940 silica

Table 6-12

Wavelength, (Microns)	Refractive Index, n	Reference
1.028	1.450	a
1.196	1.448	b
1.370	1.446	b
1.560	1.444	b
1.722	1.442	c
1.870	1.440	b
2.010	1.438	b
2.145	1.436	b
2.270	1.434	b
2.390	1.432	b
2.50	1.430	b
2.595	1.428	b

THICKNESS not stated mm

RAY ORDINARY ☒, EXTRAORDINARY ☐

WAVELENGTH 1.0 - 2.6 μ

TEMPERATURE 291 °K

METHOD not stated

REFERENCE Smakula [1952]

REMARKS References for this Table:

(a) Carvallo, A., Compt. rend., Vol. 126, (1898), p. 728.

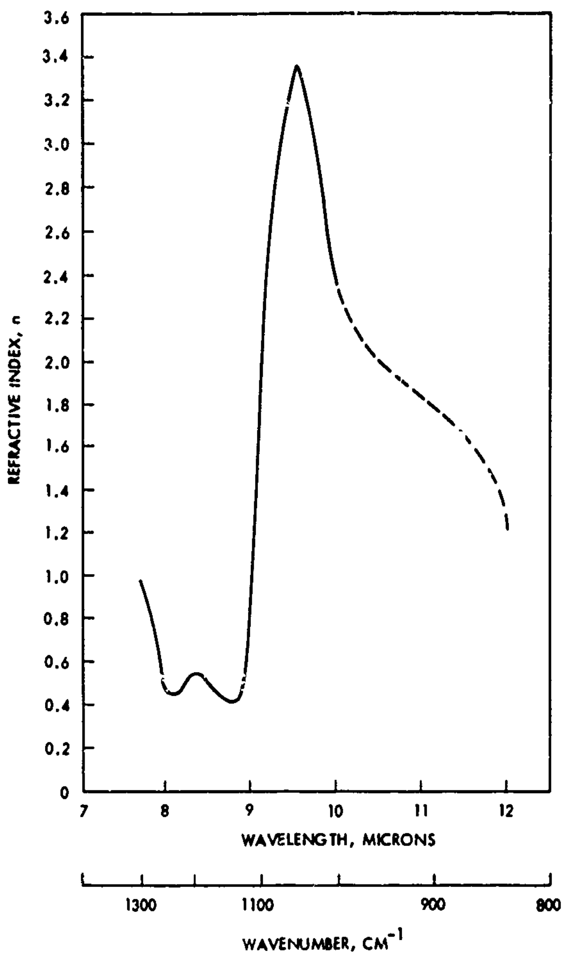
(b) Muller, C. and Wetthauer, A., Z. Phys., Vol. 35, (1933), p. 559.

(c) Sifford, J. W., Proc. Roy. Soc., Vol. 70, (1902), p. 329.

Table 6-13

PARAMETER: Wavelength

MATERIAL: Silica, Fused



FORM: Bulk

THICKNESS: 6.0 mm

RAY: ORDINARY ☒, EXTRAORDINARY ☐

WAVELENGTH: 7.7 - 12 μ

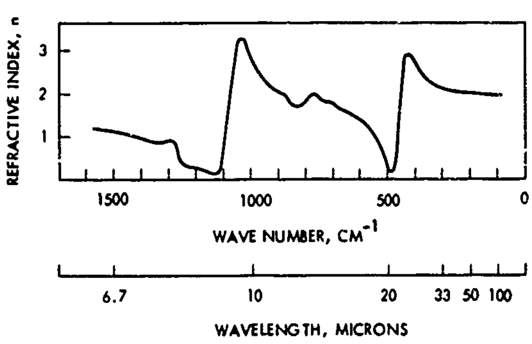
TEMPERATURE: ~298 °K

METHOD: Reflectance

REFERENCE: Cleck (27331)

REMARKS: Corning Code 7940 silica

Figure 6-19



THICKNESS: Not stated mm

RAY: ORDINARY ☒, EXTRAORDINARY ☐

WAVELENGTH: 6 - 100 μ

TEMPERATURE: 298 °K

METHOD: Reflectance

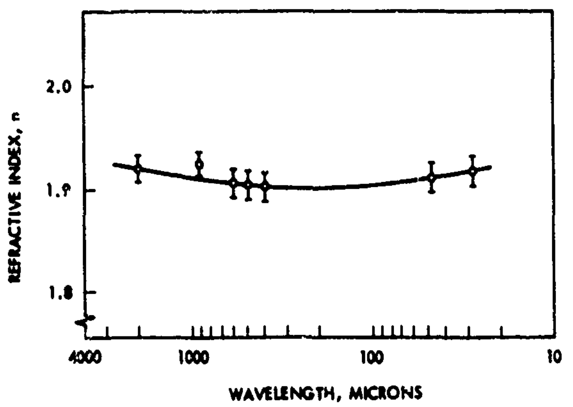
REFERENCE: Miler (21593, 34239)

REMARKS:

Figure 6-20

PARAMETER: Wavelength

MATERIAL: Silica, Fused



FORM: Not stated

THICKNESS: Not stated mm

RAY: ORDINARY ☒, EXTRAORDINARY ☐

WAVELENGTH: 30 - 2000 μ

TEMPERATURE: ~298 °K

METHOD: Reflection

REFERENCE: Block, et al. (36747)

REMARKS:

Figure 6-21

Wavelength, (Microns)	Refractive Index, n
50	2.07
90	1.94
220	1.89
250	1.92
270	1.89
330	1.92
400	1.92

THICKNESS: 50-90μ 25 mm (Bulk) mm
220-400μ 0.258 mm

RAY: ORDINARY ☒, EXTRAORDINARY ☐

WAVELENGTH: 50 - 400 μ

TEMPERATURE: ~298 °K

METHOD: Reflection, Interference

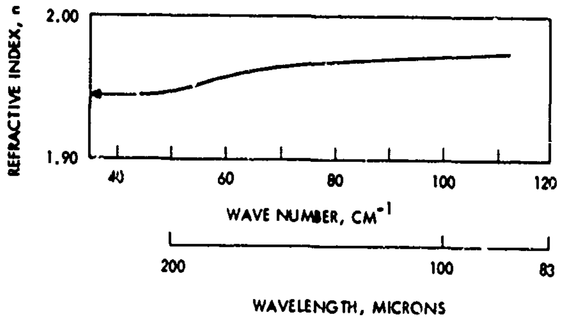
REFERENCE: Bogens and Zhukov (35268)

REMARKS:

Table 6-14

PARAMETER: Wavelength

MATERIAL: Silica, Fused



FORM Bulk

THICKNESS 0.5 mm

RAY ORDINARY ☒ EXTRAORDINARY ☐

WAVELENGTH 85 - 200 μ

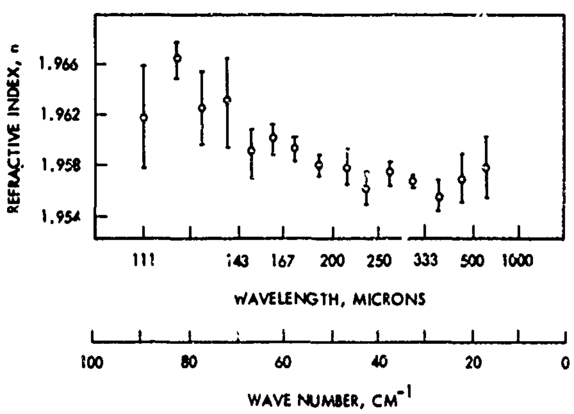
TEMPERATURE ~298 °K

METHOD Interference

REFERENCE Geick (39706)

REMARKS

Figure 6-22



THICKNESS 2.1409 mm

RAY ORDINARY ☒ , EXTRAORDINARY ☐

WAVELENGTH 111 - 600 μ

TEMPERATURE ~298 °K

METHOD Interference

REFERENCE Randall and Rawcliffe (33251)

REMARKS Infrasil low H_2O quartz

Figure 6-23

PARAMETER: Wavelength

MATERIAL: Silica, Fused

FORM Bulk

THICKNESS 18-, 40 mm

RAY ORDINARY ☒ EXTRAORDINARY ☐

WAVELENGTH 2,000 μ

TEMPERATURE ~298 °K

METHOD Transmission

REFERENCE Dianov and Irisova (41423)

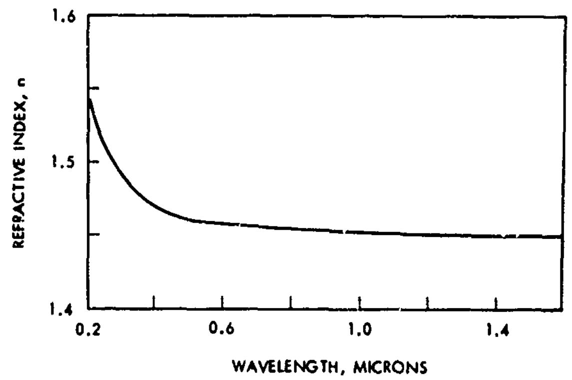
REMARKS Sample consisted of two wedges.

Wavelength, Microns	Refractive Index, n	Extinction Coefficient, $k \times 10^3$
2000	1.95 ± 0.008	0.56 ± 0.06

Table 6-15

PARAMETER: Wavelength

MATERIAL: Silica, Fused



FORM Film

THICKNESS not stated mm

RAY ORDINARY ☒ , EXTRAORDINARY ☐

WAVELENGTH 0.2 - 1.5 μ

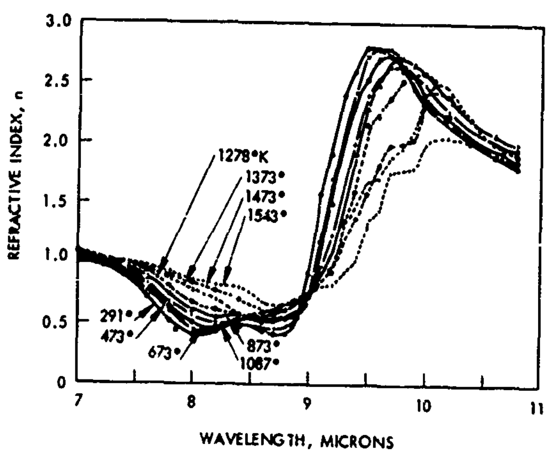
TEMPERATURE ~298 °K

METHOD Reflection

REFERENCE Cox, et al. (17066)

REMARKS Film produced by electron bombardment of fused silica, evaporated on fused silica substrate.

Figure 6-24



THICKNESS 5×10^{-4} mm

RAY ORDINARY ☒ , EXTRAORDINARY ☐

WAVELENGTH 7 - 11 μ

TEMPERATURE 291 - 1543 °K

METHOD Reflection

REFERENCE Neuroth (40354)

REMARKS

Figure 6-25

PARAMETER: Temperature

MATERIAL: Silica, Fused

Wavelength,* (Microns)	Refractive Index n 299°K	Refractive Index n 744°K	(dn/dT)/°K x 10^6	Refractive Index, n 1101°K	(dn/dT)/°K x 10^6
0.23021	1.52034	1.52908	+19.6	1.53524	+19.3
0.23783	1.51496	1.52332	+18.8	1.52985	+15.6
0.2407	1.51361	1.52201	+18.9	1.52832	+18.3
0.2465	1.50970	1.51774	+18.1	1.52391	+17.7
0.24827	1.50865	1.51665	+18.0	1.52289	+17.8
0.26520	1.50023	1.50763	+16.6	1.51351	+16.5
0.27528	1.49615	1.50327	+16.0	1.50899	+16.0
0.28035	1.49425	1.50143	+16.2	1.50691	+15.8
0.28936	1.49121	1.49818	+15.7	1.50358	+15.4
0.29673	1.48892	1.49584	+15.6	1.50112	+15.2
0.30215	1.48738	1.49407	+15.1	1.49942	+15.0
0.3130	1.48462	1.49126	+14.9	1.49641	+14.7
0.333415	1.48000	1.48633	+14.2	1.49135	+14.1
0.36502	1.47469	1.48089	+14.0	1.48563	+13.6
0.40466	1.46978	1.47575	+13.4	1.48033	+13.2
0.43584	1.46685	1.47248	+12.7	1.47716	+12.9
0.54607	1.46028	1.46575	+12.3	1.47004	+12.2
0.5780	1.45899	1.46429	+11.9	1.46870	+12.1
1.01398	1.45039	1.45562	+11.8	1.45960	+11.5
1.12866	1.44903	1.45426	+11.8	1.45820	+11.4
1.254	1.44772	1.45283	+11.5	1.45700	+11.6
1.36728	1.44635	1.45140	+11.4	1.45549	+11.4
1.470	1.44524	[illegible]	+11.4	1.45440	+11.4
1.52932	1.44444	1.44961	+11.6	1.45352	+11.3
1.660	1.44307	1.44799	+11.1	1.45174	+10.8
1.701	1.44230	1.44733	+11.3	1.45140	+11.3
1.981	1.43863	1.44361	+11.2	1.44734	+10.9
2.262	1.43430	1.43933	+11.3	1.44306	+10.9
2.553	1.42949	1.43450	+11.3	1.43854	+11.3
3.00	1.41995	1.42495	+11.2	1.42877	+11.0
3.245	1.41353	1.41893	+12.2	1.42243	+11.1
3.37*	1.40990	1.41501	+11.5	1.41915	+11.5

*Wavelength determination by narrow-bandwidth interference filters.

FORM Bulk

THICKNESS NA (Prism) mm

RAY ORDINARY ☒, EXTRAORDINARY ☐

WAVELENGTH 1.0 - 3.4 μ

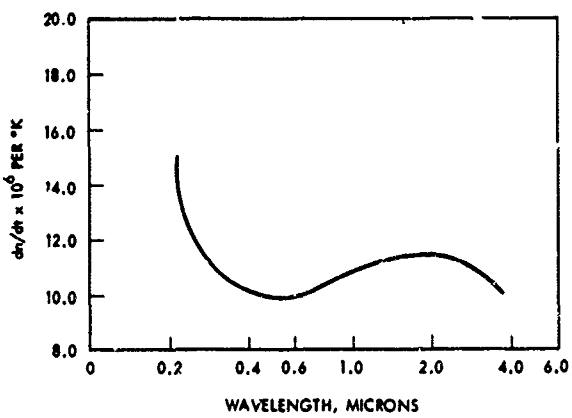
TEMPERATURE 299 - 1101 °K

METHOD Deviation

REFERENCE Neu, et al. (40360)

REMARKS Corning Code 7940 silica

Table 6-16



THICKNESS NA (Prism) mm

RAY ORDINARY ☒, EXTRAORDINARY ☐

WAVELENGTH 0.2 - 4.0 μ

TEMPERATURE 293 - 303 °K

METHOD Deviation

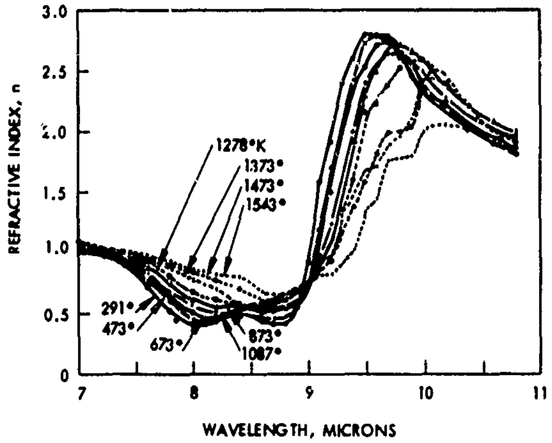
REFERENCE Malitson (21758)

REMARKS

Figure 6-26

PARAMETER: Temperature

MATERIAL: Silica, Fused



FORM Film

THICKNESS 5×10^{-4} mm

RAY ORDINARY ☒, EXTRAORDINARY ☐

WAVELENGTH 7 - 11 μ

TEMPERATURE 291 - 1543 °K

METHOD Reflection

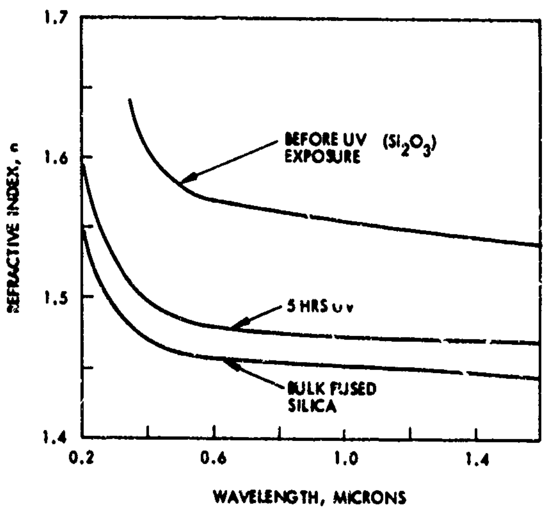
REFERENCE Neuroth (40354)

REMARKS

Figure 6-27

PARAMETER: Radiation (UV)

MATERIAL: Silica, Fused



FORM Film, Amorphous

THICKNESS $(1-5) \times 10^{-3}$ mm

RAY ORDINARY ☒, EXTRAORDINARY ☐

WAVELENGTH 0.2 - 1.5 μ

TEMPERATURE ~298 °K

METHOD Reflection

REFERENCE Cox, et al. (17066)

REMARKS Film produced by evaporation of SiO in the presence of oxygen. Data include refractive index before and after ultraviolet irradiation.

Figure 6-28

PARAMETER: Radiation (Space)

MATERIAL: Silica, Fused

Wavelength, * (Microns)	Refractive Index, n		
	Non-irradiated	Irradiated 30 day dose	$\Delta n \times 10^5$
0.23021	1.52034	1.52037	+ 3
0.23783	1.51496	1.51502	+ 6
0.2407	1.51361	1.51363	+ 2
0.2447	1.51081	1.51075	- 6
0.2465	1.50970	1.50974	+ 4
0.24827	1.50865	1.50869	+ 4
0.26520	1.50023	1.50028	+ 5
0.2700	1.49839	1.49831	- 8
0.27528	1.49615	1.49616	+ 1
0.28035	1.49425	1.49429	+ 4
0.28936	1.49121	1.49123	+ 2
0.2930	1.49021	1.49023	+ 2
0.29673	1.48892	1.48895	+ 3
0.30215	1.48738	1.48741	+ 3
0.3130	1.48462	1.48460	- 2
0.33415	1.48000	1.47997	- 3
0.36502	1.47469	1.47473	+ 4
0.40466	1.46978	1.46981	+ 3
0.43584	1.46685	1.46689	+ 4
0.54607	1.46028	1.46025	- 3
0.5780	1.45899	1.45900	+ 1
1.01398	1.45039	1.45040	+ 1
1.12866	1.44903	1.44901	- 2
1.254*	1.44772	1.44760	- 12*
1.36728	1.44635	1.44633	- 2
1.470*	1.44524	1.44513	- 11*
1.52452	1.44444	1.44445	+ 1
1.660*	1.44307	1.44296	- 11*
1.701	1.44230	1.44228	- 2
1.981*	1.43863	1.43859	- 4*
2.262*	1.43430	1.43426	- 4*
2.553*	1.42949	1.42939	- 10*
3.00*	1.41995	1.41962	- 33*
3.245*	1.41353	1.41351	- 2*
3.37*	1.40990	1.40997	+ 7*

$\delta n = 23 \times 10^{-5}$ (experimental error)

*Wavelength determination by narrow band interference filters.

FORM Bulk

THICKNESS NA (Prism) mm

RAY ORDINARY ☒, EXTRAORDINARY ☐

WAVELENGTH 0.2 - 3.4 μ

TEMPERATURE 299 °K

METHOD Deviation

REFERENCE Neu, et al. (40360)

REMARKS Corning Code 7040 silica. Radiation simulating 30 day exposure for Apollo mission.

Proton flux: 3×10^{10} cm^{-2} sec^{-1} (≤ 2 MeV). Electron flux: 2.5×10^{12} cm^{-2} sec^{-1} (1 MeV). Ultraviolet: 0.5461 watt-cm^{-2} (0.22 - 0.4 μ) Atmospheric pressure: P_{min} = 10^{-10} Torr)

Table 6-17

CHAPTER 7

REFRACTIVE INDEX DATA FOR FLUORIDES AND SELECTED CERAMICS

This Chapter provides refractive indices and extinction coefficients for the following fluorides and ceramics which are grouped together on the basis of their high temperature capabilities: Calcium fluoride, magnesium fluoride, aluminum oxide including ruby and sapphire, and magnesium oxide.

CALCIUM FLUORIDE

INTRODUCTION

Calcium fluoride offers high and uniform transmission over the range from the ultraviolet region to approximately ten microns (Figures 1-7 and 1-9) and this constant transmission makes this material very desirable for wide spectrum optical applications. Rather pure single crystal calcium fluoride is found in nature and is called "Fluorite" or "Fluorspar." Calcium fluoride of similar purity, but of larger dimensions, has been produced by controlled freezing of purified molten calcium fluoride after an initial scavenging with lead fluoride. Fluorspar is widely used in iron foundry operations, the manufacture of primary aluminum and magnesium, as source of fluorine chemicals, for the production of glass and enamels, and innumerable other uses.

The physical properties of calcium fluoride are summarized in Table 1-1.

DATA

A list of refractive index data for calcium fluoride is provided in Table 7-1 and the temperature range of the data is plotted in Figure 7-1. The wavelength dependence of the refractive index and some extinction coefficients for bulk single crystal material are presented in Figures 7-2 to 7-9 and Tables 7-2 to 7-6 and for polycrystalline material in Figure 7-10 and Tables 7-7 and 7-8. The data reveal good agreement in refractive index is discernible between single and polycrystalline material. Only in the "Reststrahlen" region of the spectrum (near 38 microns) is there a major disagreement in refractive index between authors. The temperature dependence of the refractive index is covered by Figures 2-3 and 7-11 as well as Tables 7-9 and 7-10.

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Table 7-1. List of Calcium Fluoride Data

Figure	Table	n, k	Form	Crystal	Wavelength (Microns) From	Wavelength (Microns) To	Remarks	Parameter
	7-2	n	Bulk	Single	0.75	1.1		Wavelength
	7-3	n	Bulk	Single	0.8	9.0		Wavelength
	7-4	n	Bulk	Single	0.9	9.4		Wavelength
	7-5	n	Bulk	Single	0.8	9.8		Wavelength
7-2		n	Bulk	Single	1	10		Wavelength
	7-6	n	Bulk	Single	0.85	9.7		Wavelength
7-3		k	Bulk	Single	6	9		Wavelength
7-4		n, k	Bulk	Single	15	48		Wavelength
7-5		n, k	Bulk	Single	34	43		Wavelength
7-6		n	Bulk	Single	10	80		Wavelength
7-7		k	Bulk	Single	10	80		Wavelength
7-8		n	Bulk	Single	8	15		Wavelength
7-9		n	Bulk	Single	55	400	80, 300°K	Wavelength
	7-7	n	Bulk	Polycryst.	0.59	5.3		Wavelength
	7-8	n	Bulk	Polycryst.	1	11		Wavelength
7-10		n	Bulk	Polycryst.	1	11		Wavelength
	7-9	dn/dT	Bulk	Single	0.9	6.5	330-354°K	Temperature
	7-10	dn/dT	Bulk	Single	0.85	9.7	292°K	Temperature
7-11		n	Bulk	Single	55	400	80, 300°K	Temperature

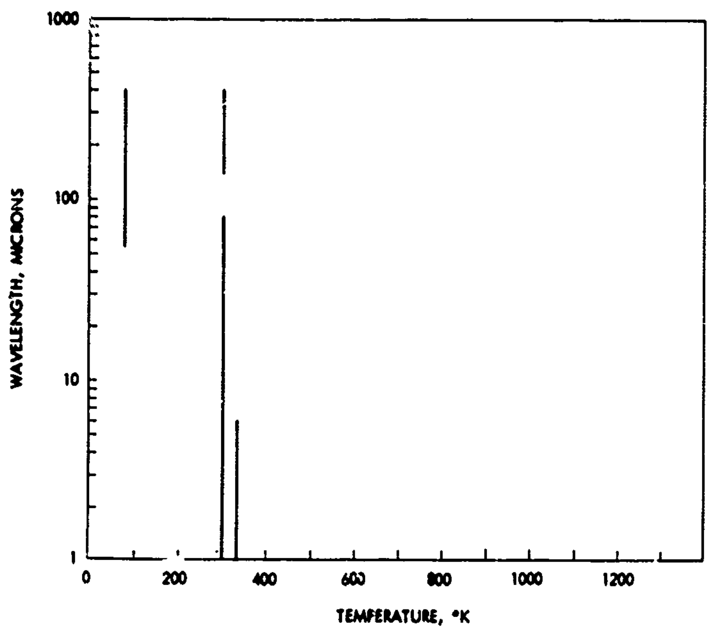


Figure 7-1. Wavelength and Temperature Range of Calcium Fluoride Data

PARAMETER: Wavelength

MATERIAL: Calcium Fluoride

Wavelength, (Microns)	Refractive Index, n	Wavelength, (Microns)	Refractive Index, n
0.750	1.43114	0.940	1.42935
0.760	1.43102	0.950	1.42927
0.770	1.43090	0.960	1.42920
0.780	1.43079	0.970	1.42913
0.790	1.43068	0.930	1.42906
0.800	1.43057	0.990	1.42899
0.810	1.43047	1.000	1.42892
0.820	1.43037	1.010	1.42885
0.830	1.43027	1.020	1.42879
0.840	1.43018	1.030	1.42872
0.850	1.43008	1.040	1.42866
0.860	1.42999	1.050	1.42859
0.870	1.42990	1.060	1.42853
0.880	1.42982	1.070	1.42847
0.890	1.42974	1.080	1.42841
0.900	1.42966	1.090	1.42835
0.910	1.42958	1.100	1.42829
0.920	1.42950	1.110	1.42823
0.930	1.42942	1.120	1.42817

FORM: Bulk (probably single crystal)

THICKNESS: Not stated mm

RAY: ORDINARY ☒, EXTRAORDINARY ☐

WAVELENGTH: 0.75 - 1.1 μ

TEMPERATURE: 293 °K

METHOD: Not stated

REFERENCE: Harting [1948]

REMARKS:

Table 7-2

Wavelength, (Microns)	Refractive Index, n	Wavelength, (Microns)	Refractive Index, n
0.80	1.430563	3.0	1.41793
0.90	1.429651	3.5	1.41412
1.00	1.428923	4.0	1.40971
1.2	1.427760	4.5	1.40469
1.4	1.426772	5.0	1.39901
1.6	1.425833	6.0	1.38562
1.8	1.424885	7.0	1.36932
2.0	1.423895	8.0	1.34988
2.3	1.422294	9.0	1.32685
2.6	1.420525		

THICKNESS: Not stated mm

RAY: ORDINARY ☒, EXTRAORDINARY ☐

WAVELENGTH: 0.8 - 9.0 μ

TEMPERATURE: 293 °K

METHOD: Not stated

REFERENCE: Smakula [1952]

REMARKS: Data taken from Kohlrausch [1943]

Table 7-3

PARAMETER: Wavelength

MATERIAL: Calcium Fluoride

Wavelength (Microns)	Refractive Index, n	Wavelength (Microns)	Refractive Index, n
0.48400	1.42980	2.800	1.41923
1.0140	1.42884	2.880	1.41890
1.08304	1.42843	2.9466	1.41825
1.1000	1.42831	3.0500	1.41750
1.1786	1.42789	3.0980	1.41714
1.250	1.42752	3.2413	1.41610
1.3756	1.42689	3.4000	1.41487
1.4733	1.42642	3.5359	1.41376
1.5715	1.42596	3.8306	1.41119
1.650	1.42558	4.000	1.40963
1.7680	1.42502	4.1252	1.40847
1.8100	1.42468	4.2500	1.40722
1.8688	1.42454	4.4000	1.40568
1.900	1.42439	4.6000	1.40357
1.9153	1.42431	4.7146	1.40233
1.9644	1.42407	4.8000	1.40130
2.0582	1.42360	5.000	1.39908
2.0626	1.42357	5.3036	1.39522
2.1608	1.42306	5.8932	1.38712
2.250	1.42258	6.4825	1.37824
2.3573	1.42198	7.0718	1.36805
2.450	1.42143	7.6612	1.35675
2.5537	1.42080	8.2505	1.34440
2.6519	1.42018	8.8398	1.33075
2.700	1.41988	9.4291	1.31605
2.750	1.41956		

FORM: Bulk

THICKNESS: Not stated mm

RAY: ORDINARY ☒ , EXTRAORDINARY ☐

WAVELENGTH: 0.9 - 9.4 μ

TEMPERATURE: 293 °K

METHOD: Not stated

REFERENCE: Ballard (12539)

REMARKS:

Table 7-4

Wavelength, (Microns)	Refractive Index n	Wavelength, (Microns)	Refractive Index n
0.80	1.43052	4.60	1.40354
0.82	1.43032	4.80	1.40130
0.84	1.43013	5.00	1.39895
0.86	1.42995	5.20	1.39650
0.88	1.42977	5.40	1.39394
0.90	1.42961	5.60	1.39127
0.92	1.42945	5.80	1.38849
0.94	1.42930	6.00	1.38559
0.96	1.42915	6.20	1.38258
0.98	1.42901	6.40	1.37945
1.00	1.42888	6.60	1.37620
1.20	1.42771	6.80	1.37282
1.40	1.42672	7.00	1.36932
1.60	1.42579	7.20	1.36569
1.80	1.42484	7.40	1.36193
2.00	1.42385	7.60	1.35804
2.20	1.42280	7.80	1.35401
2.40	1.42168	8.00	1.34983
2.60	1.42049	8.20	1.34552
2.80	1.41921	8.40	1.34106
3.00	1.41785	8.60	1.33645
3.20	1.41639	8.80	1.33169
3.40	1.41480	9.00	1.32677
3.60	1.41320	9.20	1.32168
3.80	1.41147	9.40	1.31643
4.00	1.40963	9.60	1.31101
4.20	1.40770	9.80	1.30542
4.40	1.40567		

THICKNESS: NA (Prism) mm

RAY: ORDINARY ☒ , EXTRAORDINARY ☐

WAVELENGTH: 0.8 - 9.8 μ

TEMPERATURE: 297 °K

METHOD: Deviation

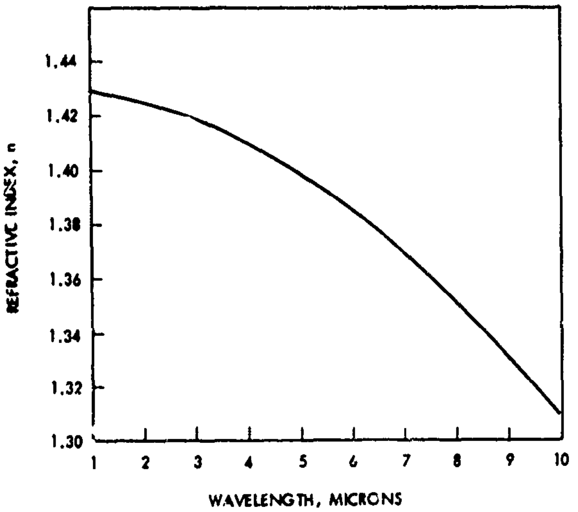
REFERENCE: Malitson (39194)

REMARKS: Computed refractive index, based on observed data.

Table 7-5

PARAMETER: Wavelength

MATERIAL: Calcium Fluoride



FORM Bulk, Single Crystal

THICKNESS NA (Prism) mm

RAY ORDINARY ☒ , EXTRAORDINARY ☐

WAVELENGTH 1 - 10 μ

TEMPERATURE 297 °K

METHOD Deviation

REFERENCE Malitson (391^4)

REMARKS Synthetic crystal

Figure 7-2

Wavelength, (Microns)	Computed Index, n	Residual [(Observed-Computed) x 10^5] Material	
		Synthetic o-c	Natural o-c
0.85212	1.43002	-1	+4
0.8944	1.42966	0	+1
1.01398	1.42879	-2	0
1.3622	1.42691	+1	+8
1.39506	1.42675	+1	+6
1.52952	1.42612	+4	+4
1.7012	1.42531	+2	+4
1.81307	1.42478	0	+9
1.97009	1.42401	+3	+3
2.1526	1.42306	-1	+1
2 32542	1.42212	+3	+4
2.4374	1.42147	0	+2
3.3026	1.41561	0	+3
3.422	1.41467	+2	+2
3.5070	1.41398	-1	+2
3.7067	1.41229	+2	+2
4.258	1.40713	+4	+4
5.01882	1.39873	+1	+5
5.3034	1.39520	+3	+3
[illegible].0140	1.3853[illegible]	+5	+5
6.238	1.38200	-6	0
6.63306	1.37565	0	+1
6.8559	1.37186	-8	+2
7.268	1.36443	+2	+7
7.4644	1.36070	+5	+6
8.662	1.33500	-4	+3
9.724	1.30756	+1	+5

THICKNESS NA (Prism) mm

RAY ORDINARY ☒ , EXTRAORDINARY ☐

WAVELENGTH 1 - 10 μ

TEMPERATURE 297 °K

METHOD Deviation

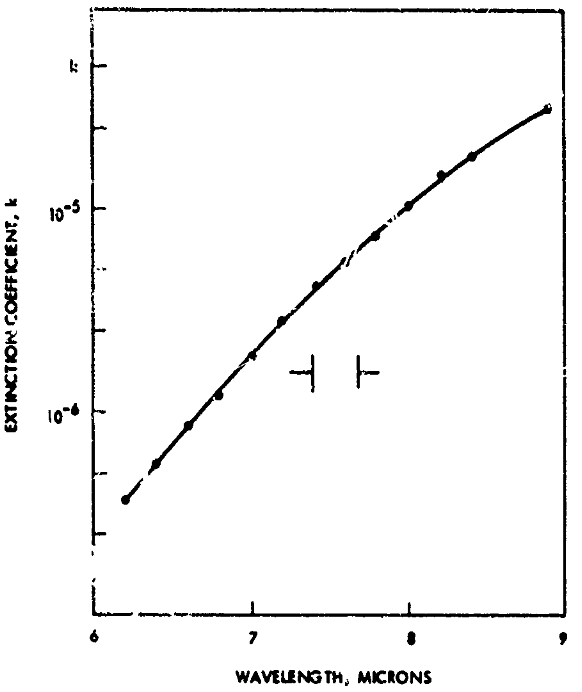
REFERENCE Malitson (39194)

REMARKS Comparison of natural and synthetic single crystals

Table 7-6

PARAMETER: Wavelength

MATERIAL: Calcium Fluoride



FORM Bulk, Single Crystal

THICKNESS 111.7(6-9μ), 8 (15-48μ) mm

RAY ORDINARY ☒, EXTRAORDINARY ☐

WAVELENGTH 6 - 48 μ

TEMPERATURE ~298 °K

METHOD 6-9μ-Transmission; 15-48μ Reflection.

REFERENCE Heilmann (40178)

REMARKS Improved results over earlier work, reported by Heilmann [1961]

Figure 7-3

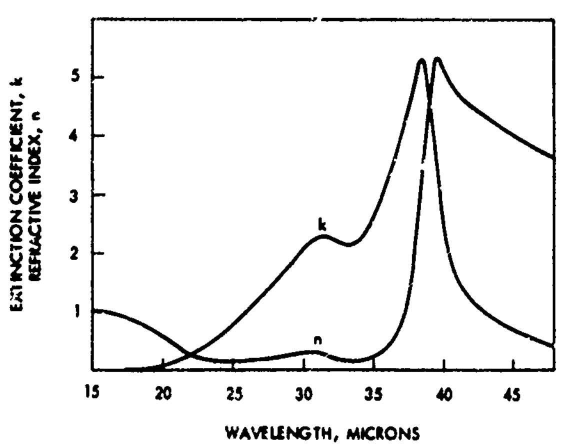


Figure 7-4

PARAMETER: Wavelength (Cont'd from preceding page) MATERIAL: Calcium Flouride

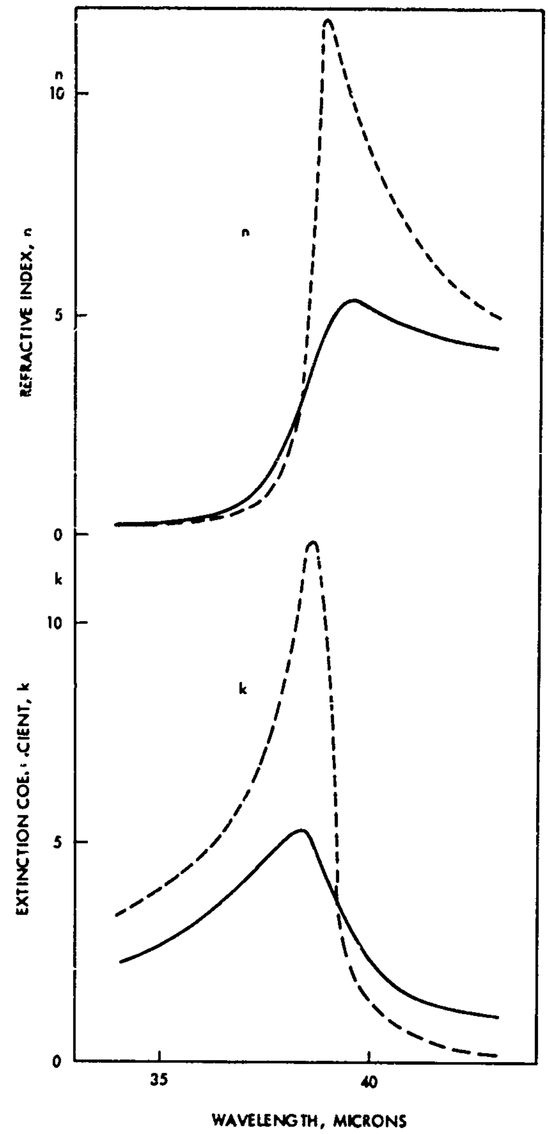
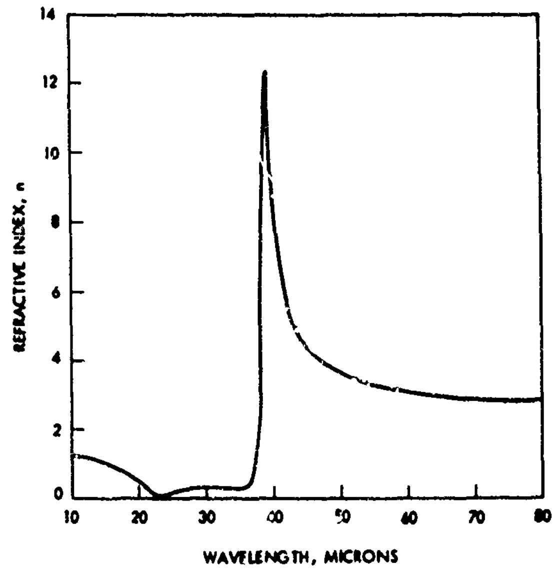


Figure 7-5

Note: ----- Results of Kaiser, et al (40176).

PARAMETER: Wavelength

MATERIAL: Calcium Fluoride



FORM Bulk, Single Crystal

THICKNESS 0.1 - 5 mm

RAY ORDINARY ☒, EXTRAORDINARY ☐

WAVELENGTH 10 - 80 μ

TEMPERATURE ~298 °K

METHOD Reflection

REFERENCE Kaiser, et al. (40176)

REMARKS

Figure 7-6

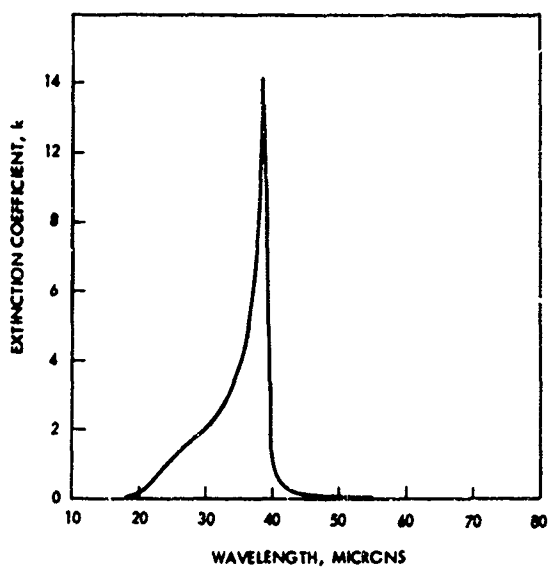
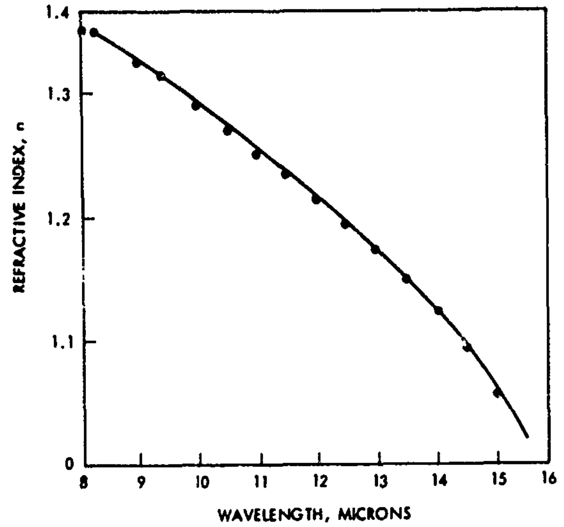


Figure 7-7

PARAMETER: Wavelength

MATERIAL: Calcium Fluoride



FORM Bulk, Single Crystal

THICKNESS 0.025 - 0.050 mm

RAY ORDINARY ☒, EXTRAORDINARY ☐

WAVELENGTH 8 - 15 μ

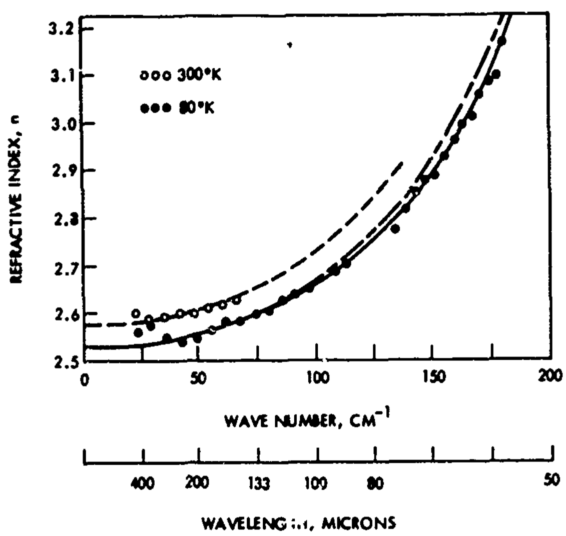
TEMPERATURE ~298 °K

METHOD Interference

REFERENCE Ramadier - Delbès (39712)

REMARKS

Figure 7-8



THICKNESS 0.3 - 10 mm

RAY ORDINARY ☒, EXTRAORDINARY ☐

WAVELENGTH 55 - 400 μ

TEMPERATURE 80, 300 °K

METHOD Interference

REFERENCE Bosomworth (029681)

REMARKS Principal impurity 10-100 ppm of iron. Lines are based on dielectric constant of an infinite harmonic fluorite lattice.

Figure 7-9

PARAMETER: Wavelength

MATERIAL: Calcium Fluoride

Wavelength, (Microns)	Refractive Index, n
0.588	1.4339
1.014	1.4289
1.529	1.4262
1.970	1.4241
2.325	1.4222
2.674	1.4200
3.303	1.4157
4.258	1.4072
4.59	1.4034
5.303	1.3952

FORM Bulk, Polycrystalline

THICKNESS Not stated mm

RAY ORDINARY ☒, EXTRAORDINARY ☐

WAVELENGTH 0.59 - 5.3 μ

TEMPERATURE ~298 °K

METHOD Not stated

REFERENCE Type IRG 12 material

REMARKS

Table 7-7

Wavelength, (Microns)	Refractive Index, n	Wavelength, (Microns)	Refractive Index, n
1.000	1.4289	5.7300	1.3892
1.2500	1.4275	6.0000	1.3856
1.5000	1.4263	6.2500	1.3818
1.7500	1.4251	6.5000	1.3778
2.0000	1.4239	6.7500	1.3737
2.2500	1.4226	7.0000	1.3693
2.5000	1.4211	7.2500	1.3648
2.7500	1.4196	7.5000	1.3600
3.0000	1.4179	7.7500	1.3550
3.2500	1.4161	8.0000	1.3498
3.5000	1.4141	8.2500	1.3445
3.7500	1.4120	8.5000	1.3388
4.0000	1.4097	8.7500	1.3330
4.2500	1.4072	9.0000	1.3269
4.50000	1.4047	9.2500	1.3206
4.7500	1.4019	9.5000	1.3141
5.0000	1.3990	9.7500	1.3073
5.2500	1.3959	10.0000	1.3002
5.5000	1.3926	11.0000	1.2694

THICKNESS Not stated mm

RAY ORDINARY ☒, EXTRAORDINARY ☐

WAVELENGTH 1 - 11 μ

TEMPERATURE 298 °K

METHOD Not stated

REFERENCE Kodak [1967]

REMARKS ITRAN-3 material

Table 7-8

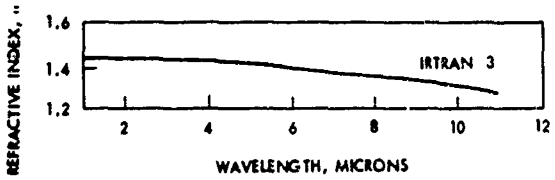


Figure 7-10

PARAMETER: Temperature

MATERIAL: Calcium Fluoride

Wavelength (Microns)	Temperature Coefficient, $-(dn/dT) \times 10^6$	Mean Temperature, °K
0.900	10.31	333.1
1.200	10.40	333.1
1.25	10.29	333.2
1.30	10.18	333.5
2.0	9.32	333.5
3.16	8.81	332.6
4.2	8.31	332.8
5.3	8.21	332.2
6.5	7.87	330.0

FORM Bulk, Single Crystal

THICKNESS Not stated mm

RAY **ORDINARY** ☒ , **EXTRAORDINARY** ☐

WAVELENGTH 0.9 - 6.5 μ

TEMPERATURE 330 - 335 °K

METHOD Not stated

REFERENCE Smakula [1952]

REMARKS Data taken from Liebreich [1911]

Table 7-9

Wavelength, (Microns)	Computed Index, n	Temperature Coefficient, $-(dn/dT) \times 10^6$
0.85212	1.43002	10.6
0.8944	1.42966	10.6
1.01398	1.42879	10.5
1.39506	1.42675	9.9
1.52952	1.42612	9.6
1.7012	1.42531	9.4
1.81307	1.42478	9.1
1.97009	1.42401	8.9
2.1526	1.42306	8.7
2.32542	1.42212	8.5
2.4374	1.42147	8.5
3.3026	1.41561	8.2
3.422	1.41467	8.1
3.5070	1.41398	8.0
3.7067	1.41229	7.8
4.258	1.40713	7.5
5.01882	1.39873	7.3
5.3034	1.39520	7.2
6.0140	1.38539	7.0
6.238	1.38200	7.0
6.63306	1.37565	6.9
6.8559	1.37186	6.7
7.268	· 36443	6.5
7.4644	1.36070	6.4
8.662	1.33500	6.0
9.724	1.30756	5.6

THICKNESS NA (Prism) mm

RAY **ORDINARY** ☒ , **EXTRAORDINARY** ☐

WAVELENGTH 0.85 - 9.7 μ

TEMPERATURE 292 °K

METHOD Deviation

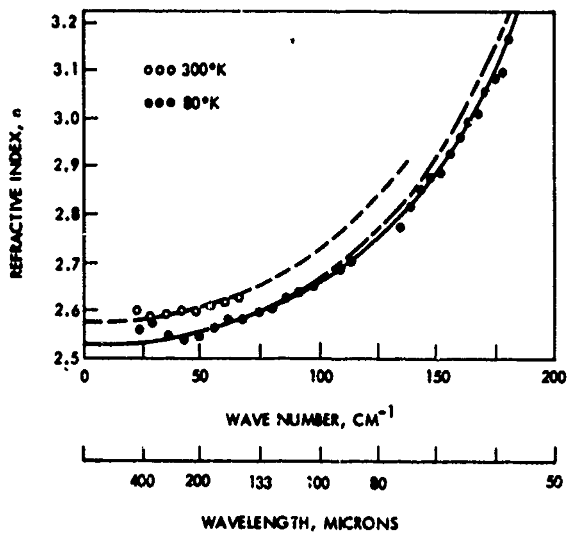
REFERENCE Malitson (39194)

REMARKS Synthetic single crystal.

Table 7-10

PARAMETER: Temperature

MATERIAL: Calcium Fluoride



FORM Bulk, Single Crystal

THICKNESS 0.3 - 10 mm

RAY ORDINARY ☒, EXTRAORDINARY ☐

WAVELENGTH 55 - 400 μ

TEMPERATURE 80, 300 °K

METHOD Interference

REFERENCE Bosomworth (29681)

REMARKS Principal impurity 10-100 ppm of iron. Lines are based on dielectric constant of an infinite harmonic fluorite lattice.

Figure 7-11

MAGNESIUM FLUORIDE

INTRODUCTION

Magnesium fluoride is prepared by the reaction of magnesium oxide with hydrofluoric acid and as a byproduct from the reduction of metal fluorides with magnesium in the manufacture of some metals. Magnesium fluoride is used as flux in the metallurgy of magnesium metal, as flux for porcelain and pottery, as phosphor in cathode ray screens, as coating agent for titanium pigments, and in optics as window material and antireflection coating on lenses.

The optical transmission of polycrystalline magnesium fluoride is shown in Figure 1-9, and its physical properties are listed in Table 1-1.

DATA

Refractive index data for magnesium fluoride are listed in Table 7-11 and consist only of one set of data for polycrystalline material (Figure 7-12 and Table 7-12) and one data point for magnesium fluoride film (Table 7-13). This apparent lack of data in the literature does not permit a comparison of results.

Table 7-11. List of Magnesium Fluoride Data

Figure	Table	n, k	Form	Crystal	Wavelength (Microns) From	Wavelength (Microns) To	Parameter
	7-12	n	Bulk	Polycryst	1.0	6.75	Wavelength
7-12		n	Bulk	Polycryst	1	9	Wavelength
	7-13	n	Film	*	2.0	2.0	Wavelength

*Not Stated

PARAMETER: Wavelength

MATERIAL: Magnesium Fluoride

Wavelength, (Microns)	Refractive Index, n	Wavelength, (Microns)	Refractive Index. n
1.0000	1.3778	4.0000	1.3526
1.2500	1.3763	4.2500	1.3492
1.5000	1.3749	4.5000	1.3455
1.7500	1.3735	4.7500	1.3416
2.0000	1.3720	5.0000	1.3374
2.2500	1.3702	5.2500	1.3329
2.5000	1.3683	5.5000	1.3282
2.7500	1.3663	5.7500	1.3232
3.0000	1.3640	6.0000	1.3179
3.2500	1.3614	6.2500	1.3122
3.5000	1.3587	6.5000	1.3063
3.7500	1.3558	6.7500	1.3000

FORM Bulk, Polycrystalline

THICKNESS Not stated mm

RAY ORDINARY ☒, EXTRAORDINARY ☐

WAVELENGTH 1 - 9 µ

TEMPERATURE 298 °K

METHOD Not stated

REFERENCE Kodak [1967]

REMARKS IRTRAN-1 material

Table 7-12

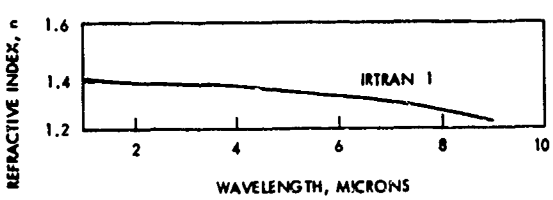


Figure 7-12

PARAMETER: Wavelength

MATERIAL: Magnesium Fluoride

Wavelength, Microns	Refractive Index, n_o
2	1.36

FORM Film

THICKNESS $\sim 5 \times 10^{-4}$ mm

RAY ORDINARY ☒, EXTRAORDINARY ☐

WAVELENGTH ~2 μ

TEMPERATURE ~298 °K

METHOD Transmission

REFERENCE Jenness (40476)

REMARKS Evaporated coating on fused silica substrate. Extraordinary ray neglected.

Table 7-13

ALUMINUM OXIDE – CORUNDUM – SAPPHIRE – RUBY

INTRODUCTION

Corundum is a naturally-occurring α-alumina, (Al_2O_3), which crystallizes in the hexagonal form. Pure corundum is fully transparent and water-white, and is called "white sapphire." Corundum for optical applications is generally synthesized and called "sapphire." Corundum crystals containing from approximately 0.04 to 5 percent chromic oxide in their lattices are called "ruby." The ruby's applications in optics are mostly in laser technology. The synthesis of sapphire is commonly performed by means of the Verneuil or flame fusion process which is based on the fusion of the aluminum oxide with heat from a hydrogen-oxygen source and growth at a controlled temperature of approximately 2300°K. The light transmission through sapphire is shown in Figure 1-8 and shows a useful region between 0.2 and 5 microns. The infrared optical properties of corundum, sapphire and ruby are essentially identical, [Ref. Haefele (9762)].

Physical properties of sapphire are summarized in Table 1-1. Uses for aluminum oxide include gems, jewel bearings, luminescent materials, abrasives and optics.

DATA

A list of data presentations for aluminum oxide is offered in Table 7-14 and the wavelength- and temperature coverage is plotted in Figure 7-13. The spectral dependence of the refractive index of bulk corundum, sapphire and ruby is shown in Figures 7-14 to 7-22 and Tables 7-15 to 7-17 for ordinary and extraordinary rays with inclusion of some extinction coefficients. The data show good agreement among authors and materials. Data for amorphous films are presented in Figures 7-23 and 7-24 with fair agreement of the sparse data with bulk data. Table 7-18 gives refractive index data as a function of wavelength and anodizing potential, and it is apparent

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that low anodizing potentials give high readings — more nearly resembling the metal than the oxide. The temperature dependence of the refractive index is covered by Figures 7-25 and 7-26 as well as Tables 7-19 and 7-20.

Table 7-14. List of Aluminum Oxide Data

Figure	Table	n, k	Form	Crystal	Wavelength (Microns) From	To	Remarks	Parameter
7-14		n, k	Bulk	Corundum	9	33	293°K	Wavelength
7-15		n, k	Bulk	Corundum	9	33	1773°K	Wavelength
7-16		n	Bulk	Sapphire	0.3	5.6		Wavelength
	7-15	n	Bulk	Sapphire	2.0	3.6		Wavelength
7-17		n	Bulk	Sapphire	58	500	O-ray	Wavelength
7-18		n	Bulk	Sapphire	58	500	E-ray	Wavelength
7-19		n	Bulk	Sapphire	180	500	O & E-rays	Wavelength
	7-16	n	Bulk	Sapphire	58	500	O & E-rays	Wavelength
7-20		n	Bulk	Sapphire	112	300		Wavelength
	7-17	n	Bulk	Sapphire	167	500	O & E-rays	Wavelength
7-21		n, k	Bulk	Ruby	6	33	O-ray	Wavelength
7-22		n, k	Bulk	Ruby	6	33	E-ray	Wavelength
	7-1[illegible]	n	Film	Amorphous	1.5	[illegible]5		Wavelength
7-23		n	Film	Amorphous	0.2	[illegible].6	318°K, 573°K	Wavelength
7-24		n	Film	Amorphous	15	57		Wavelength
7-25		n, k	Bulk	Corundum	9	33	293°K	Temperature
7-26		n, k	Bulk	Corundum	9	33	1773°K	Temperature
	7-19	n	Bulk	Sapphire	0.56	4.0	296 — 1973°K	Temperature
	7-20	dn/dT	Bulk	Sapphire	4	4	292 — 297°K	Temperature

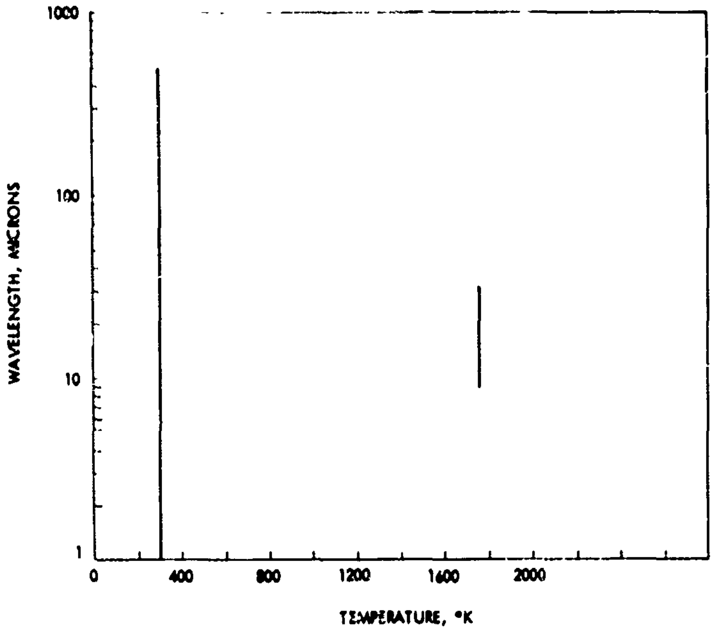
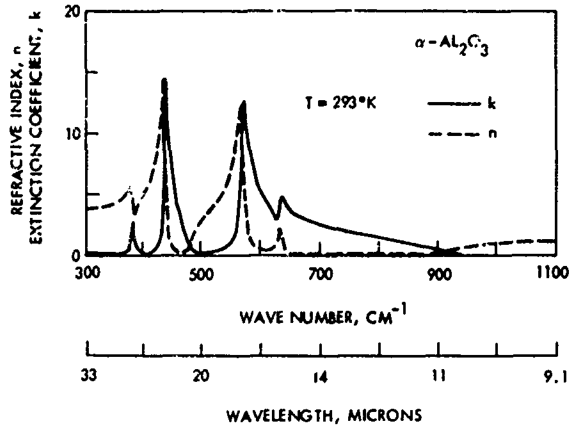


Figure 7-13. Wavelength and Temperature Range of Aluminum Oxide Data

PARAMETER: Wavelength

MATERIAL: Aluminum Oxide-Corundum



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FORM Bulk, Single Crystal

THICKNESS Not stated mm

RAY ORDINARY ☒, EXTRAORDINARY ☐

WAVELENGTH 9 – 33 μ

TEMPERATURE 293, 1773 °K

METHOD Reflection

REFERENCE Piriou (29797)

REMARKS

Figure 7-14

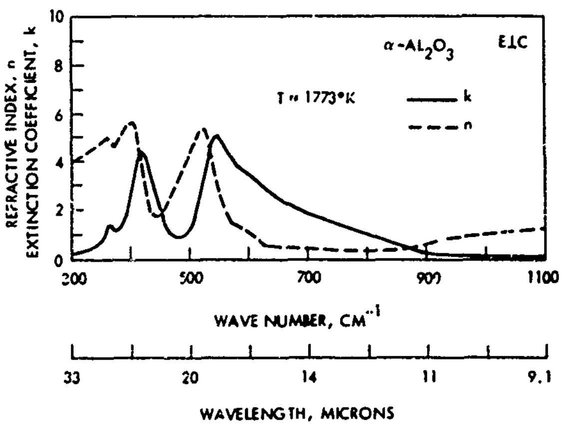

Figure 7-15

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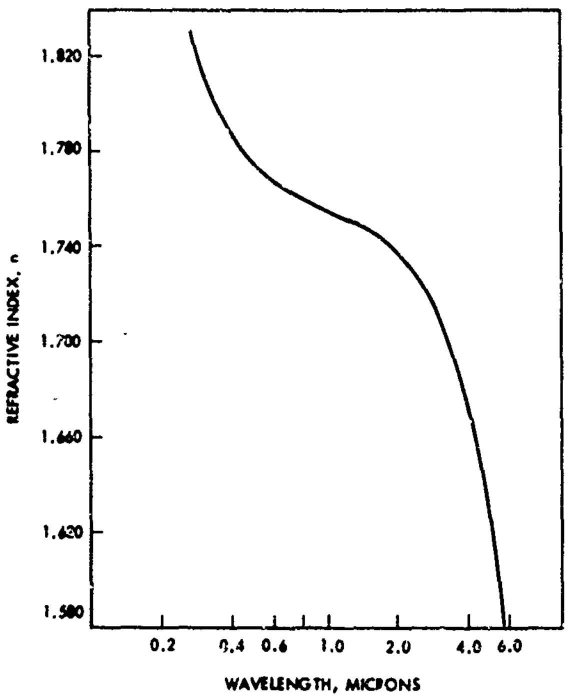
PARAMETER: Wavelength

MATERIAL: Aluminum Oxide-Sapphire



FORM Bulk, Single Crystal

THICKNESS NA (Prism) mm

RAY ORDINARY ☒, EXTRAORDINARY ☐

WAVELENGTH 0.3 – 5.6 μ

TEMPERATURE 297 °K

METHOD Deviation

REFERENCE Malitson (17008)

REMARKS

Figure 7-16

Wavelength, (Microns)	Refractive Index, n
2.0	1.65
3.6	1.60

THICKNESS 1.6, 3.2 mm

RAY ORDINARY ☒, EXTRAORDINARY ☐

WAVELENGTH 2.0, 3.6 μ

TEMPERATURE ~298 °K

METHOD Transmission

REFERENCE Jenness (40476)

REMARKS Values estimated from LiF coating data

Table 7-15

PARAMETER: Wavelength

MATERIAL: Aluminum Oxide-Sapphire

FORM Bulk, Single Crystal

THICKNESS 1.0 mm

RAY ORDINARY ☒ , EXTRAORDINARY ☐

WAVELENGTH 58 - 500 μ

TEMPERATURE 301 °K

METHOD Interference

REFERENCE Russell & Bell (28755)

REMARKS

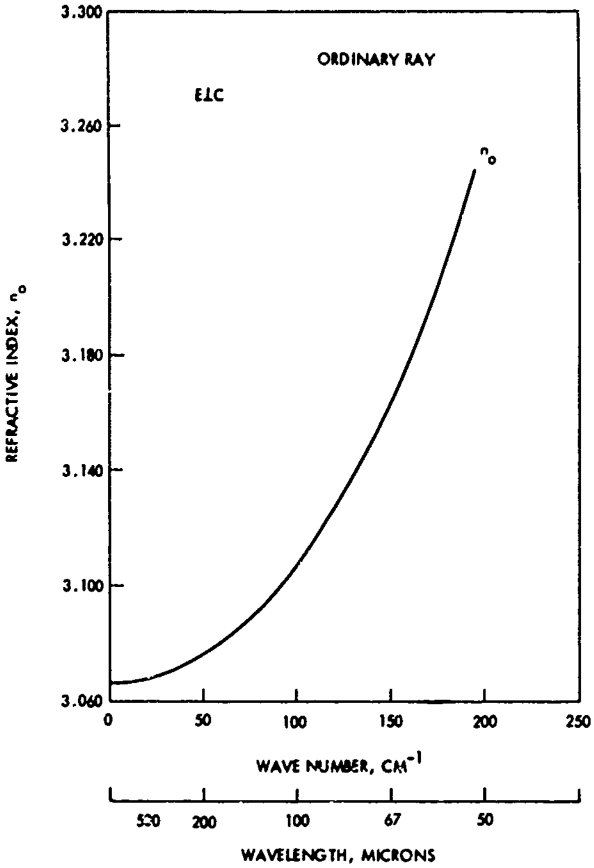


Figure 7-17

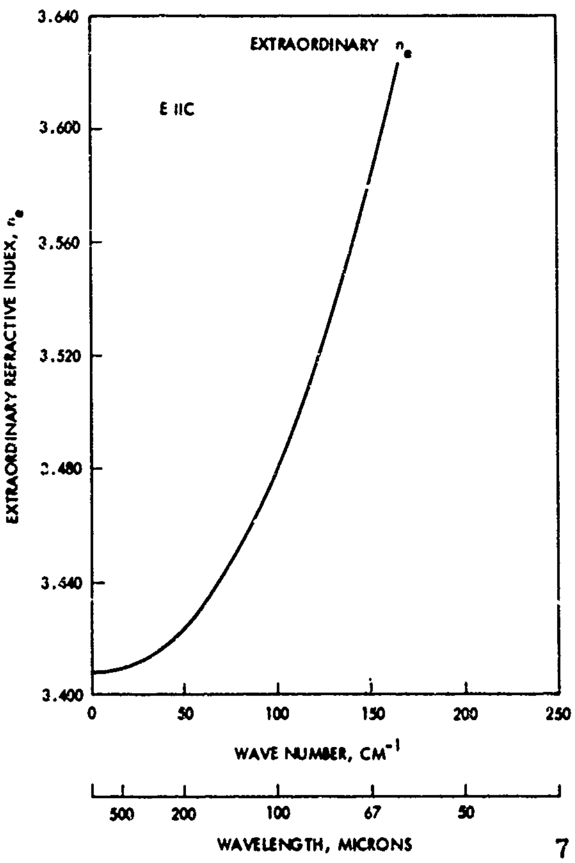


Figure 7-18

PARAMETER: Wavelength (Cont'd from preceding page)

MATERIAL: Aluminum Oxide-Sapphire

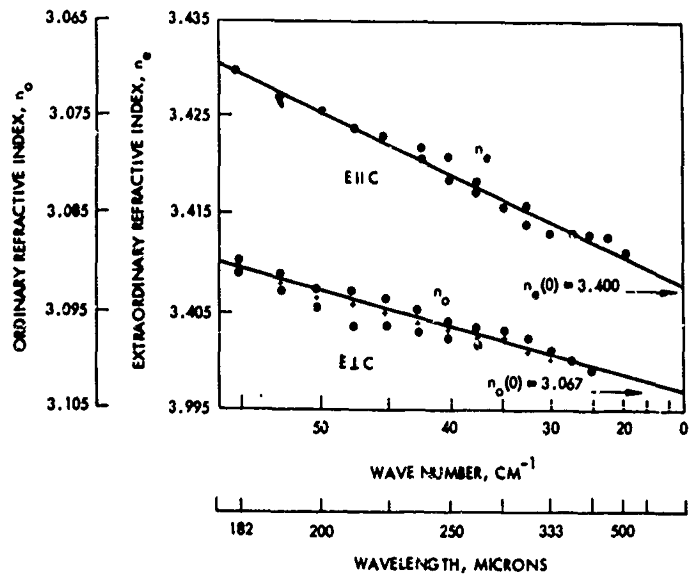


Figure 7-19

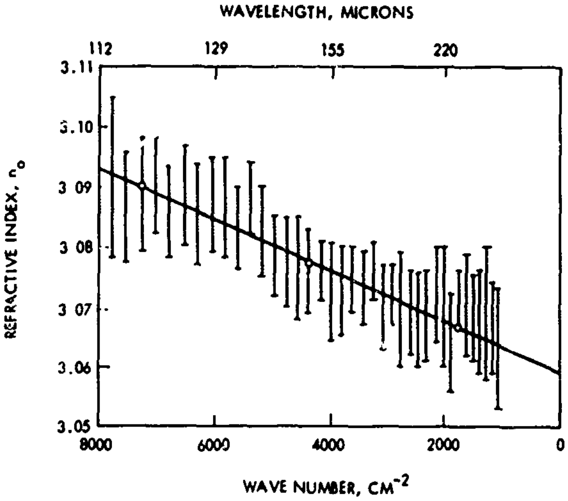
Table 7-16

Wave Number cm^{-1}	Wavelength, (Microns)	Refractive Indices[a]		
		n_o	n_e	$n_e - n_o$
20.2		3.0688	3.4111	0.3423
25.2		3.0698	3.4129	0.3436
30.2	330	3.0704	3.4134	0.3430
35.3		3.0720	3.4163	0.3443
40.3		3.0740	3.4187	0.3447
45.4		3.0752	3.4232	0.3480
50.4	200	3.0770	3.4260	0.3490
55.4		3.0795	3.4294	0.3499
60.5		3.0822	3.4334	0.3512
65.5		3.0843	3.4391	0.3548
70.6	142	3.0870	3.4444	0.3574
75.6		3.0906	3.4510	0.3604
80.6		3.0941	3.4569	0.3628
85.7		3.0982	3.4625	0.3643
90.7		3.1019	3.4689	0.3670
95.8		3.1060	3.4766	0.3706
100.8	100	3.1103	3.4836	0.3733
105.8		3.1147	3.4908	0.3761
110.9		3.1198	3.4993	0.3795
115.9		3.1249	3.5081	0.3832
120.9	83	3.1304	3.5185	0.3881
126.0		3.1357	3.5279	0.3922
131.0		3.1422	3.5375	0.3953
136.1		3.1485	3.5508	0.4023
141.1	71	3.1549	3.5612	0.4063
146.1		3.1623	3.5746	0.4123
151.2		3.1696	3.5856	0.4160
156.2	64	3.1765	3.6042	0.4277
161.3		3.1854		
166.3		3.1921		
171.3		3.2018		
176.4	57	3.2113		

[a] The total estimated probable error of the measured values of the refractive indices is ±0.002 except at frequencies less than 25 cm^{-1} and greater than 150 cm^{-1} where the error may be somewhat greater.

PARAMETER: Wavelength

MATERIAL: Aluminum Oxide-Sapphire



FORM Bulk, Single Crystal

THICKNESS 1.0 mm

RAY ORDINARY ☒, EXTRAORDINARY ☐

WAVELENGTH 112 - 300 μ

TEMPERATURE ~298 °K

METHOD Transmission

REFERENCE Roberts & Coon (18253)

REMARKS

Figure 7-20

Wavelength, (Microns)	Refractive Index,	
	n_o	n_e
167-500	3.14 ± 4%	3.61 ± 4%

THICKNESS 1.0 mm

RAY ORDINARY ☒, EXTRAORDINARY ☐

WAVELENGTH 167 - 500 μ

TEMPERATURE 300 °K

METHOD Interference

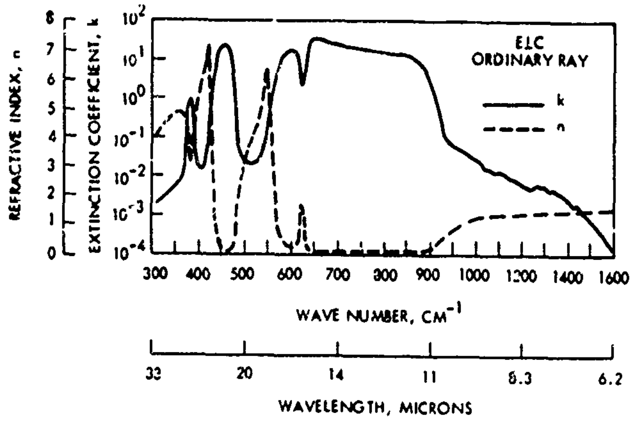
REFERENCE Loewenstein (17012)

REMARKS

Table 7-17

PARAMETER: Wavelength

MATERIAL: Aluminum Oxide-Ruby



FORM Bulk, Single Crystal

THICKNESS 0.036 -6 (absorption,) 5 (reflection). mm

RAY ORDINARY ☒, EXTRAORDINARY ☐

WAVELENGTH 6 - 33 μ

TEMPERATURE ~298 °K

METHOD Absorption, Reflection

REFERENCE Haefele (9762)

REMARKS Synthetic material; containing 0.04% Cr; data held valid from 0 to 0.5% Cr.

Figure 7-21

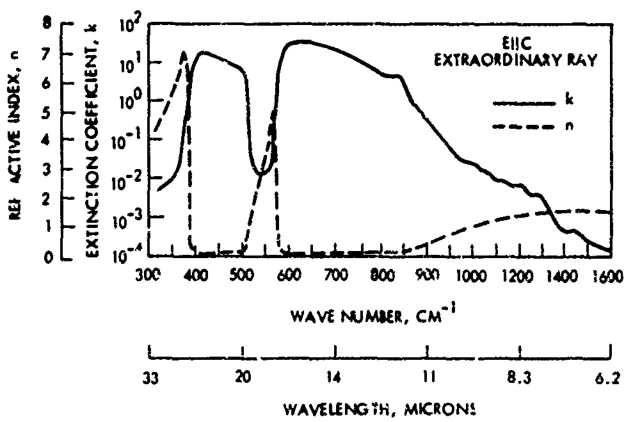


Figure 7-22

PARAMETER: Wavelength

MATERIAL: Aluminum Oxide, Amorphous

Wavelength (microns)	Anodizing Potential, Volts		
	50 volts Refractive Index, n	100 volts n	200 volts n
1.5	1.63	1.65	1.60
2	1.68±0.05	1.64±0.02	1.57±0.02
3	1.64	1.62	1.52
4	1.67	1.53	
5	1.63	1.51	1.49
6	1.66	1.45	1.43
7	1.67	1.43±01	1.37±0.03
8	1.63	1.42	1.29
9	1.70	1.40	1.26
10	1.75±0.28	1.51	1.31
11	1.77	1.55	1.48
12	1.89	1.73	1.65
13	2.04±0.6	1.86±0.4	1.76±0.12
14	2.19	1.94	1.81
15	2.55±0.3	2.04±0.3	1.91±0.2

FORM Film

THICKNESS $(0.7 - 2.8)\times10^{-4}$ mm

RAY ORDINARY ☒, EXTRAORDINARY ☐

WAVELENGTH 1.5 - 15 μ

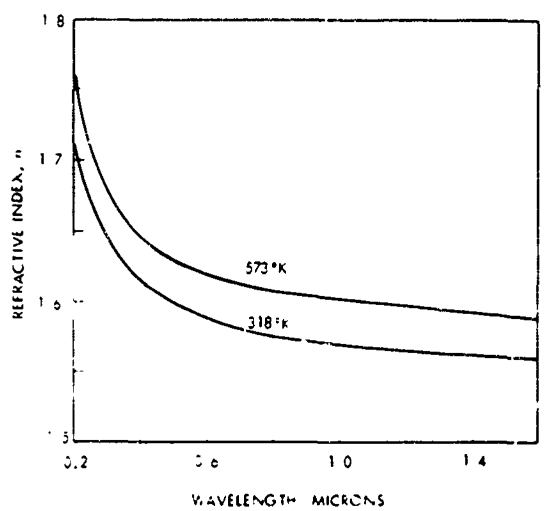
TEMPERATURE ~298 °K

METHOD Reflection

REFERENCE Harris (17011)

REMARKS Thin anodized film, removed from aluminum substrate and mounted on glass.

Table 7-18.



THICKNESS $(2-5)\times10^{-3}$ mm

RAY ORDINARY ☒, EXTRAORDINARY ☐

WAVELENGTH 0.2 - 1.6 μ

TEMPERATURE 298 °K

METHOD Reflection

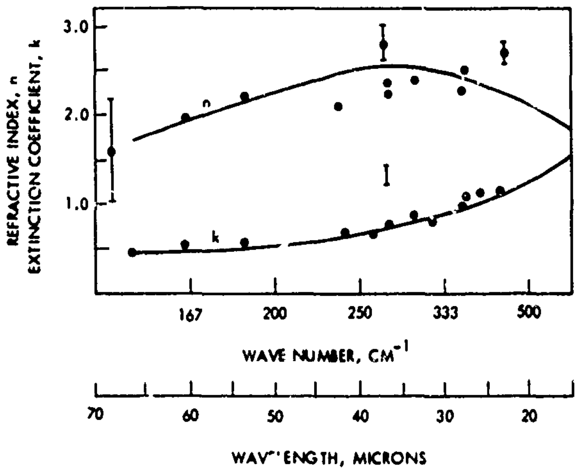
REFERENCE Cox, et al. (17066)

REMARKS Aluminum oxide produced by electron bombardment; substrate temperature as indicated.

Figure 7-23

PARAMETER: Wavelength

MATERIAL: Aluminum Oxide Amorphous



FORM Film

THICKNESS (0.7 -2.8)x10^{-4} mm

RAY ORDINARY ☒, EXTRAORDINARY ☐

WAVELENGTH 15 - 67 μ

TEMPERATURE ~298 °K

METHOD Reflection, Transmission

REFERENCE Harris & Piper (5212)

REMARKS Sputtered film

Figure 7-24

PARAMETER: Temperature

MATERIAL: Aluminum Oxide Corundum

FORM Bulk, Single Crystal

THICKNESS Not stated mm

RAY ORDINARY ☒, EXTRAORDINARY ☐

WAVELENGTH 9 - 33 μ

TEMPERATURE 293, 1773 °K

METHOD Reflection

REFERENCE Piriou (29797)

REMARKS

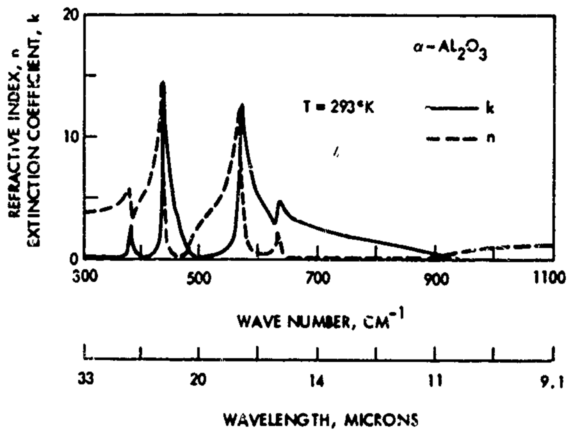


Figure 7-25

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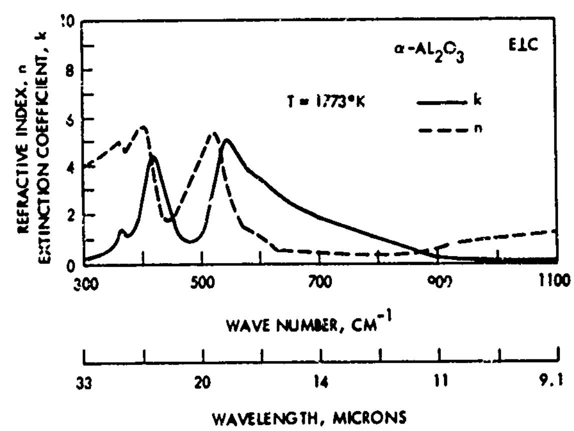


Figure 7-26

PARAMETER: Temperature

MATERIAL: Aluminum Oxide-Sapphire

"n" increases 0.05 (+0.01, -0.03) between 296 and 1973°K in the region from 0.56 to 4.0 microns.

FORM Bulk, Single Crystal

THICKNESS 1 mm

RAY ORDINARY ☒, EXTRAORDINARY ☐

WAVELENGTH 0.56 - 4.0 μ

TEMPERATURE 296 - 1973 °K

METHOD Reflection

REFERENCE Gryvnak & Burch (21068)

REMARKS Similar results were obtained for polycrystalline material.

Table 7-19

$dn/dT = 1.0 \times 10^{-5} \, °K^{-1}$

THICKNESS NA (Prism) mm

RAY ORDINARY ☒, EXTRAORDINARY ☐

WAVELENGTH ~4 μ

TEMPERATURE 292, 297 °K

METHOD Deviation

REFERENCE Malitson (17008)

REMARKS

Table 7-20

MAGNESIUM OXIDE

INTRODUCTION

Magnesium oxide has a relatively uniform optical transmission over the range from one to six microns (Figure 1-9) and excellent high temperature characteristics. Some significant physical properties of magnesium oxide are listed in Table 1-1. Magnesium oxide is found in nature as Periclase. Magnesium oxide (magnesia) for industrial applications is often produced by precipitation of magnesium hydroxide from sea water with subsequent thermal decomposition to the oxide. Single crystals for optical use may be prepared by the submerged arc-melting process in which the unmelted material serves as its own crucible. In addition to uses of magnesium oxide in optics, the material is widely used in the manufacture of refractories, fertilizers, in the rubber industry and innumerable other applications.

DATA

A list of data presentations on magnesium oxide is provided in Table 7-21 and temperature ranges are plotted in Figure 7-27. The wide range of temperatures from 8 to 2225°K is indicative of the environment that this material may have to endure. Refractive index and extinction coefficient data for single crystal magnesium oxide are presented as a function of wavelength in Figures 7-28 to 7-38 and Tables 7-22 and 7-23, while polycrystalline magnesium oxide is covered in Figure 7-39 and Table 7-24. The data show good agreement among various authors as well as between single and poly-crystalline material. The temperature dependence of the refractive index and extinction coefficient is the topic of Figures 7-40 to 7-46.

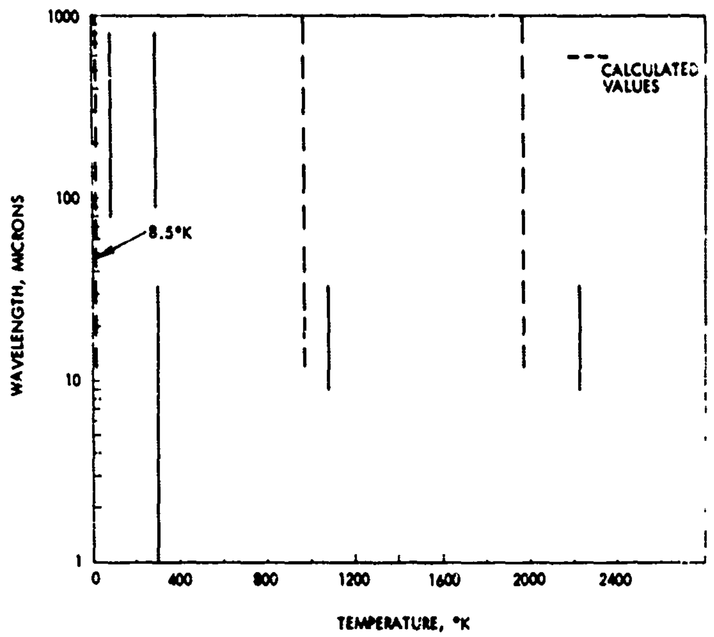


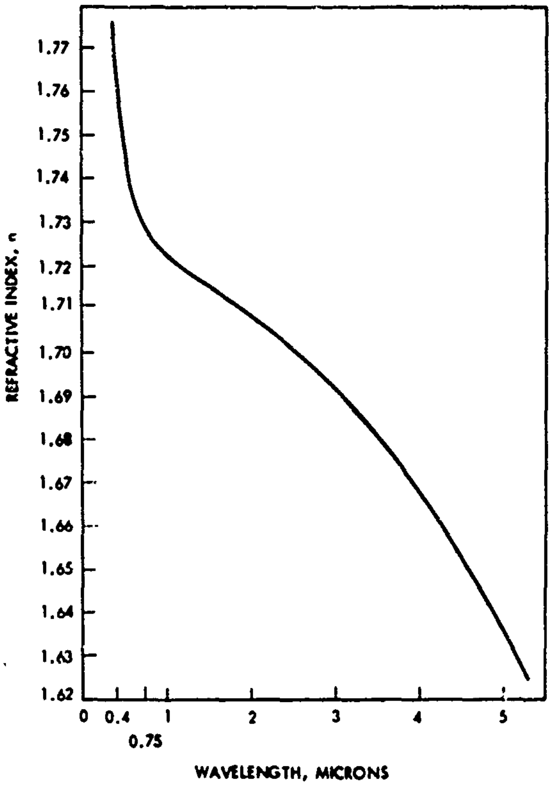
Figure 7-27. Wavelength and Temperature Range of Magnesium Oxide Data

Table 7-21

Figure	Table	n, k	Form	Crystal	Wavelength (Microns) From	Wavelength (Microns) To	Remarks	Parameter
7-28		n	Bulk	Single	0.36	5.35		Wavelength
	7-22	n	Bulk	Single	0.36	5.35		Wavelength
	7-23	n	Bulk	Single	0.7	5.4		Wavelength
7-29		n	Bulk	Single	7.0	33.0		Wavelength
7-30		n	Bulk	Single	7.0	25.0		Wavelength
7-31		k	Bulk	Single	7.0	25.0		Wavelength
7-32		n, k	Bulk	Single	9.0	33.0	293°K	Wavelength
7-33		n, k	Bulk	Single	9.0	33.0	1080°K	Wavelength
7-34		n, k	Bulk	Single	9.0	33.0	2225°K	Wavelength
7-35		n	Bulk	Single	12.0	100.0	8-1950°K	Wavelength
7-36		k	Bulk	Single	12.0	100.0	8-1950°K	Wavelength
7-37		n	Bulk	Single	90.0	800.0	90, 300°K	Wavelength
7-38		k	Bulk	Single	90.0	800.0	90, 300°K	Wavelength
7-39		n	Bulk	Polycryst	1.0	9.0		Wavelength
	7-24	n	Bulk	Polycryst	1.0	20.0		Wavelength
7-40		n, k	Bulk	Single	9.0	33.0	293°K	Temperature
7-41		n, k	Bulk	Single	9.0	33.0	1080°K	Temperature
7-42		n, k	Bulk	Single	9.0	33.0	2225°K	Temperature
7-43		n	Bulk	Single	12.0	100.0	8-1950°K	Temperature
7-44		k	Bulk	Single	12.0	100.0	8-1950°K	Temperature
7-45		n	Bulk	Single	90.0	800.0	90, 300°K	Temperature
7-46		k	Bulk	Single	90.0	800.0	90, 300°K	Temperature

PARAMETER: Wavelength

MATERIAL: Magnesium Oxide



FORM Bulk, Single Crystal

THICKNESS NA (Prism) mm

RAY ORDINARY ☒, EXTRAORDINARY ☐

WAVELENGTH 0.36 - 5.35 μ

TEMPERATURE 296.5 °K

METHOD Deviation

REFERENCE Stephens and Malitson (34823)

REMARKS

Figure 7-28

Wavelength, (Microns)	Index of Refraction, n
1.01398	1.72259
1.12866	1.72059
1.36728	1.71715
1.52952	1.71496
1.6932	1.71281
1.7092	1.71258
1.81307	1.71108
1.97009	1.70885
2.24929	1.70470
2.32542	1.70350
3.3033	1.68526
3.5078	1.66055
4.258	1.66039
5.138	1.63138
5.35	1.62404

Table 7-22

PARAMETER: Wavelength

MATERIAL: Magnesium Oxide

Wavelength, (Microns)	Refractive Index, n
0.6907	1.73191
1.0140	1.7226
1.9701	1.70885
3.3033	1.68526
4.2580	1.66039
5.3500	1.62404

FORM Bulk, Single Crystal

THICKNESS not stated mm

RAY ORDINARY ☒, EXTRAORDINARY ☐

WAVELENGTH 0.7 - 5.4 μ

TEMPERATURE ~298 °K

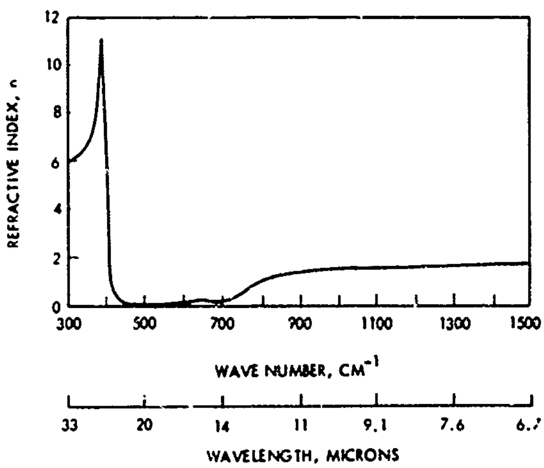
METHOD not stated

REFERENCE Norton (16227)

REMARKS Magnorite®, Norton Co.

Typical analysis: 99.7 percent MgO, 0.03 percent SiO_2, 0.04 percent CaO, 0.05 percent Fe_2O_3, 0.10 percent R_2O_3 (other than Fe_2O_3).

Table 7-23



THICKNESS 0.05 - 10 mm

RAY ORDINARY ☒, EXTRAORDINARY ☐

WAVELENGTH 7 - 33 μ

TEMPERATURE 298 °K

METHOD Reflection

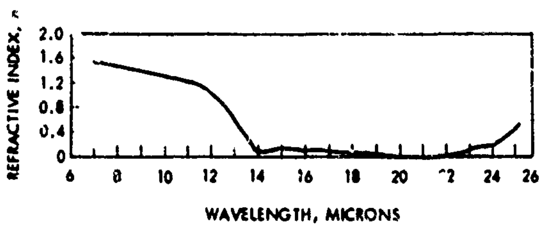
REFERENCE Haefele (34826)

REMARKS

Figure 7-29

PARAMETER: Wavelength

MATERIAL: Magnesium Oxide



FORM Bulk, Single Crystal

THICKNESS 0.076 - 0.468 mm

RAY ORDINARY ☒, EXTRAORDINARY ☐

WAVELENGTH 7 - 25 μ

TEMPERATURE ~298 °K

METHOD Reflection

REFERENCE Willmott (34804)

REMARKS Samples cleaved from massive crystal.

Figure 7-30

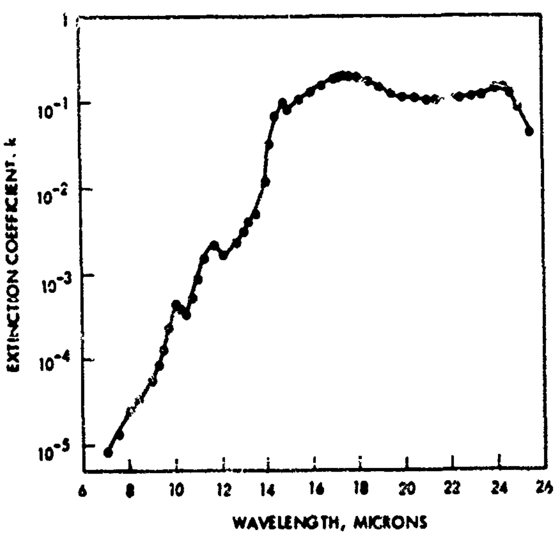


Figure 7-31

PARAMETER: Wavelength

MATERIAL: Magnesium Oxide

FORM Bulk, Single Crystal

THICKNESS not stated mm

RAY ORDINARY ☒, EXTRAORDINARY ☐

WAVELENGTH 9 - 33 μ

TEMPERATURE 293 - 2225 °K

METHOD Reflection

REFERENCE Piriou (29797)

REMARKS

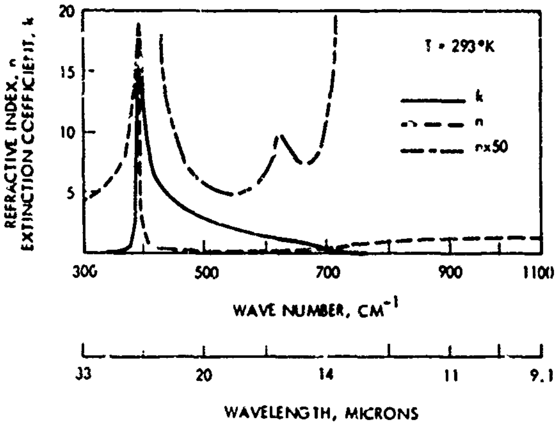


Figure 7-32

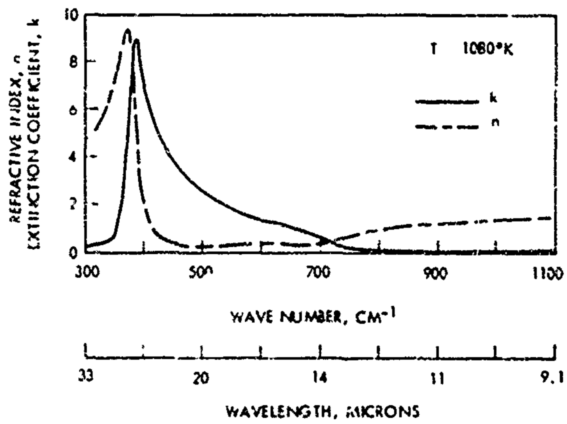


Figure 7-33

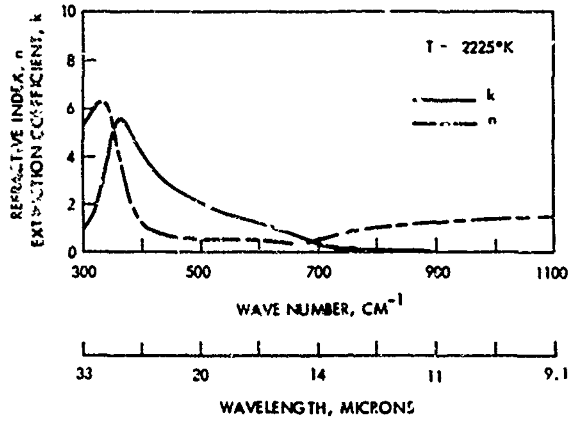


Figure 7-34

PARAMETER: Wavelength

MATERIAL: Magnesium Oxide

FORM Bulk, Single Crystal

THICKNESS not stated mm

RAY ORDINARY ☒ , EXTRAORDINARY ☐

WAVELENGTH 12 - 100 μ

TEMPERATURE 8 - 1950 °K

METHOD Reflection

REFERENCE Jasperse, et al. (34832)

REMARKS

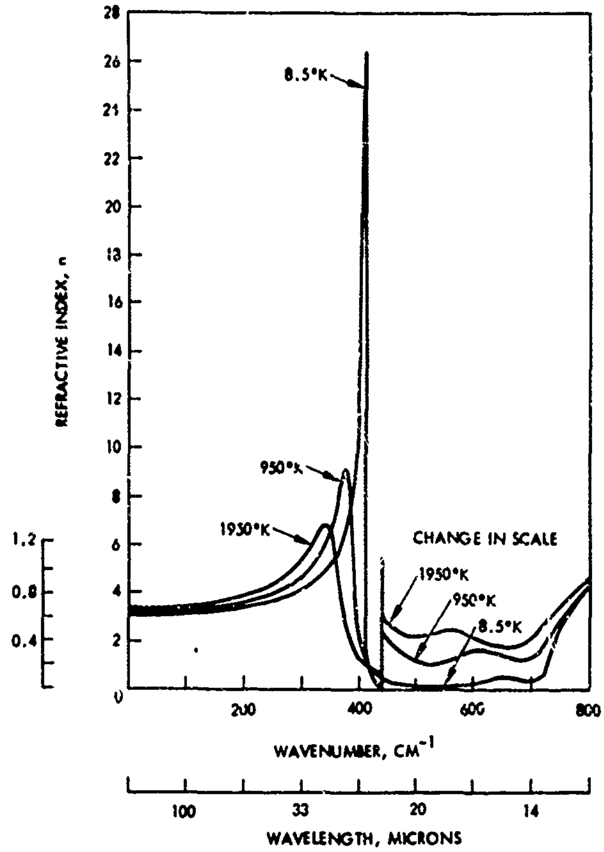


Figure 7-35

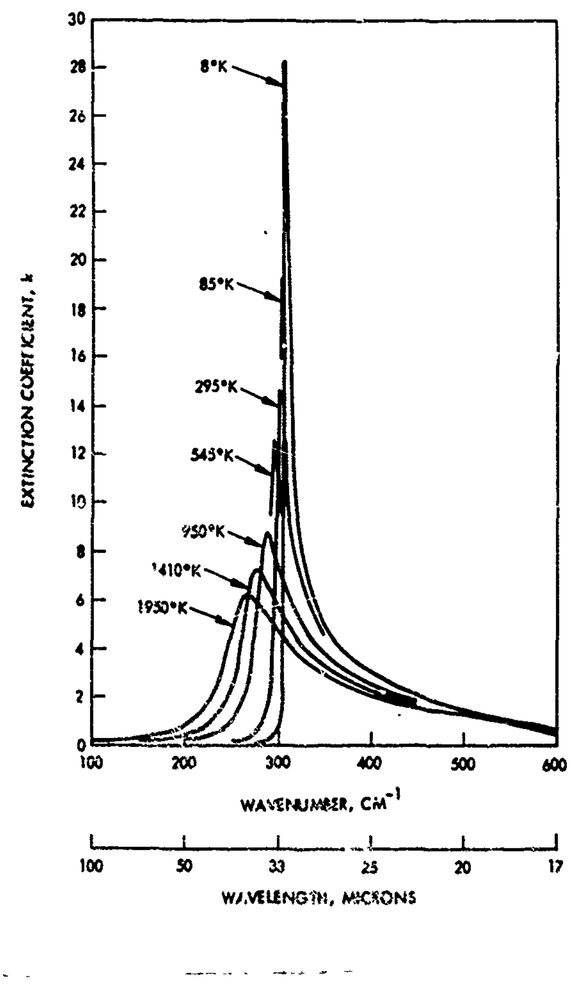


Figure 7-36

PARAMETER: Wavelength

MATERIAL: Magnesium Oxide

FORM Bulk, Single Crystal

THICKNESS 0.436, 0.693 mm

RAY ORDINARY ☒, EXTRAORDINARY ☐

WAVELENGTH 90 - 800 μ

TEMPERATURE 90, 300 °K

METHOD Transmission

REFERENCE Rowntree (34819)

REMARKS

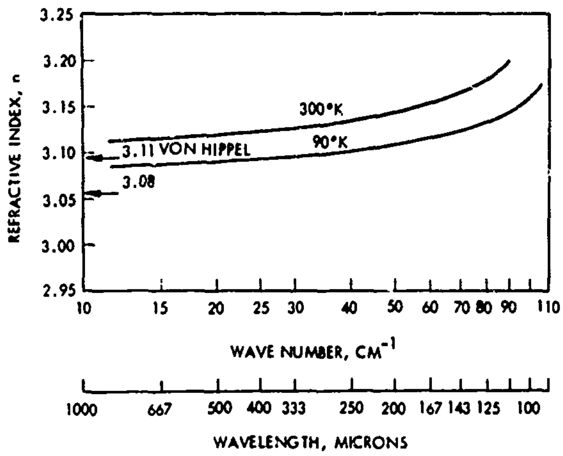


Figure 7-37

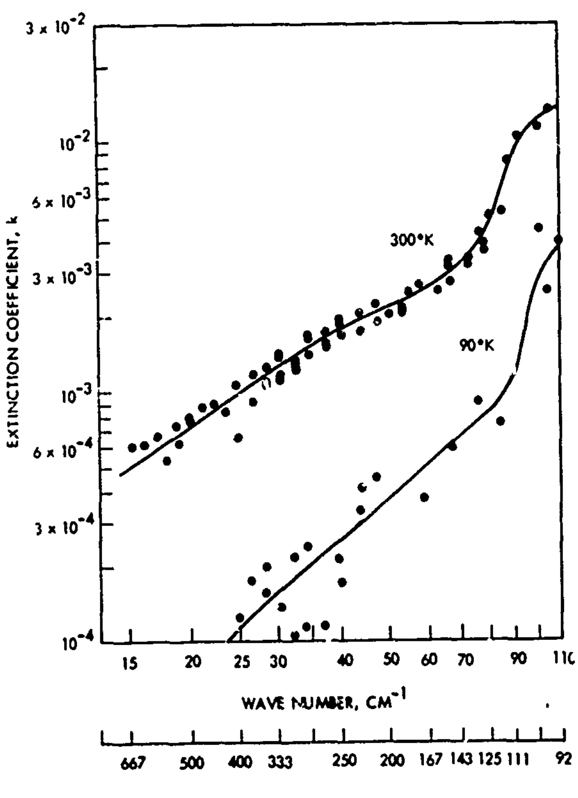
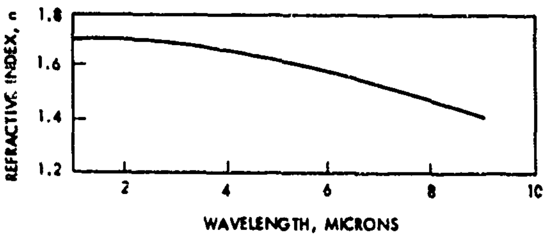


Figure 7-38

PARAMETER: Wavelength

MATERIAL: Magnesium Oxide



FORM: Bulk, Polycrystalline

THICKNESS: Not Stated mm

RAY: ORDINARY ☒, EXTRAORDINARY ☐

WAVELENGTH: 1 - 20 μ

TEMPERATURE: 298 °K

METHOD: Not Stated

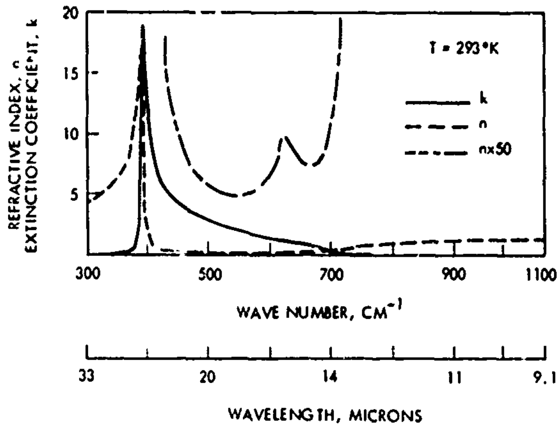
REFERENCE: Kodak [1967]

REMARKS: IRTRAN-5 material

Figure 7-39

Wavelength, (Microns)	Refractive Index, n	Wavelength, (Microns)	Refractive Index, n
1.0000	1.7227	4.2500	1.6612
1.2500	1.7188	4.5000	1.6536
1.5000	1.7156	4.7500	1.6455
1.7500	1.7123	5.0000	1.6368
2.0000	1.7089	5.2500	1.6275
2.2500	1.7052	5.5000	1.6177
2.5000	1.7012	5.7500	1.6072
2.7500	1.6968	6.0000	1.5962
3.0000	1.6920	6.2500	1.5845
3.2500	1.6868	6.5000	1.5721
3.5000	1.6811	6.7500	1.5590
3.7500	1.6750	7.0000	1.5452
4.0000	1.6684	7.2500	1.5307
		7.7500	1.5154
		7.7500	1.4993
		8.0000	1.4824

Table 7-24



FORM Bulk, Single Crystal

THICKNESS Not Stated mm

RAY ORDINARY ☒, EXTRAORDINARY ☐

WAVELENGTH 9 - 33 μ

TEMPERATURE 293 - 2225 °K

METHOD Reflection

REFERENCE Piriou (29797)

REMARKS

Figure 7-40

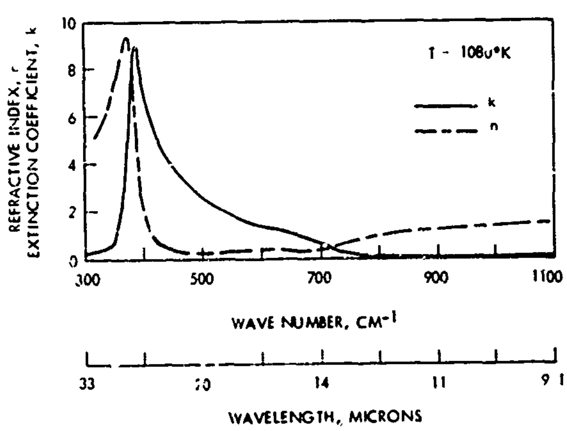


Figure 7-41

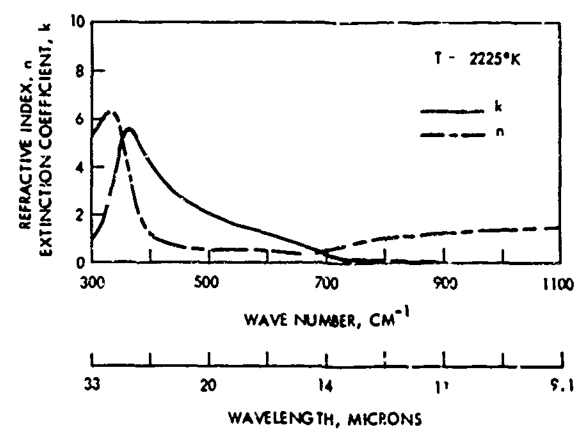


Figure 7-42

PARAMETER: Temperature

MATERIAL: Magnesium Oxide

FORM Bulk, Single Crystal

THICKNESS Not Stated mm

RAY ORDINARY ☒ , EXTRAORDINARY ☐

WAVELENGTH 12 - 100 μ

TEMPERATURE 8 - 1950 °K

METHOD Reflection

REFERENCE Jasperse, et al (34832)

REMARKS

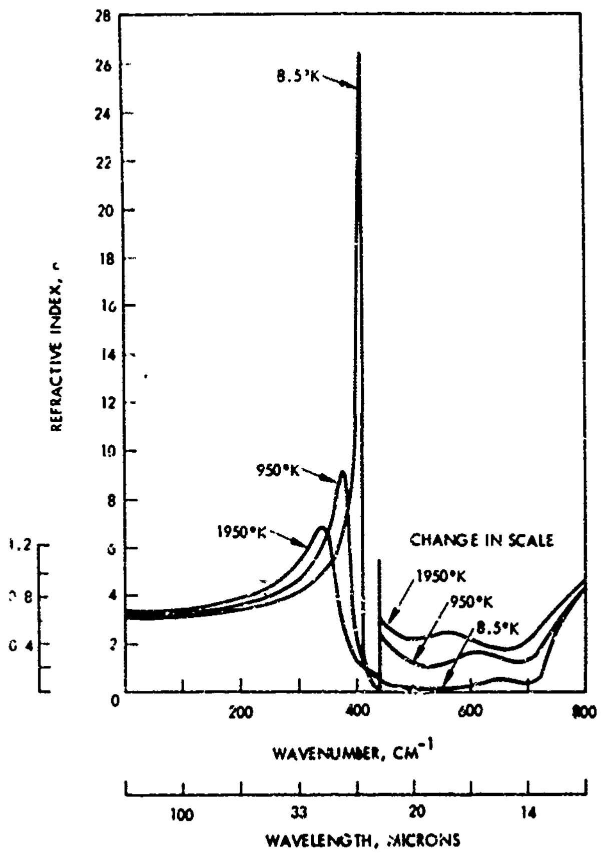


Figure 7-43

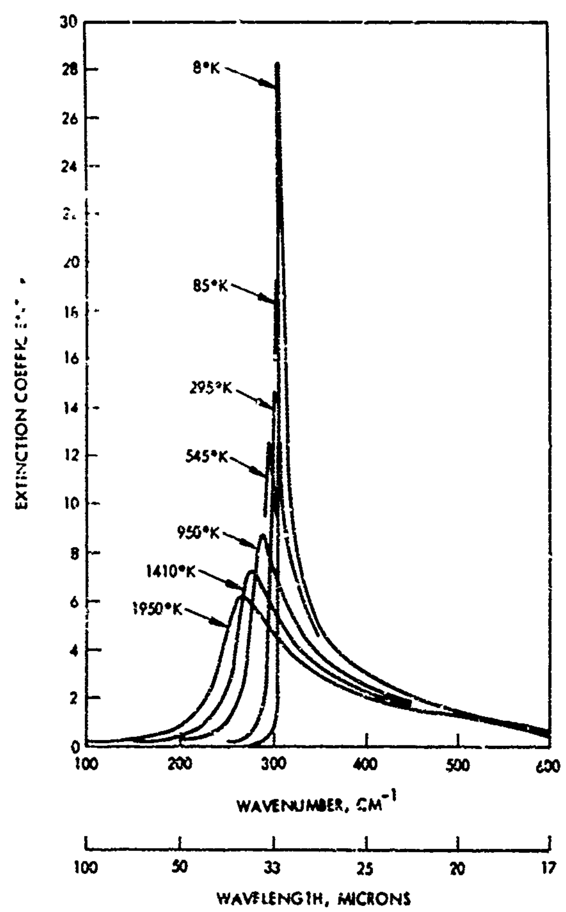


Figure 7-44

PARAMETER: Temperature

MATERIAL: Magnesium Oxide

FORM Bulk, Single Crystal

THICKNESS 0.436, 0.693 mm

RAY ORDINARY ☒ , EXTRAORDINARY ☐

WAVELENGTH 90 - 800 μ

TEMPERATURE 90, 300 °K

METHOD Transmission

REFERENCE Rowntree (34819)

REMARKS

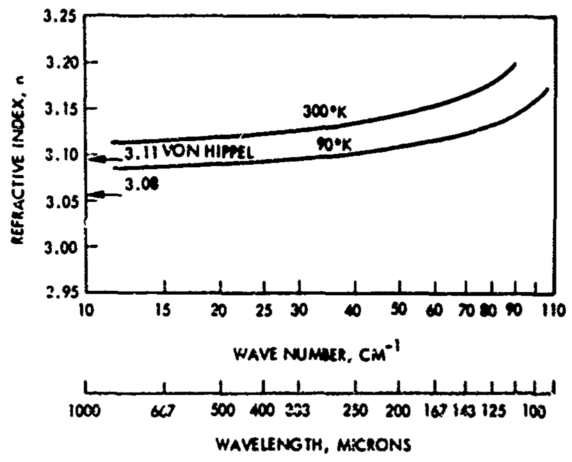


Figure 7-45

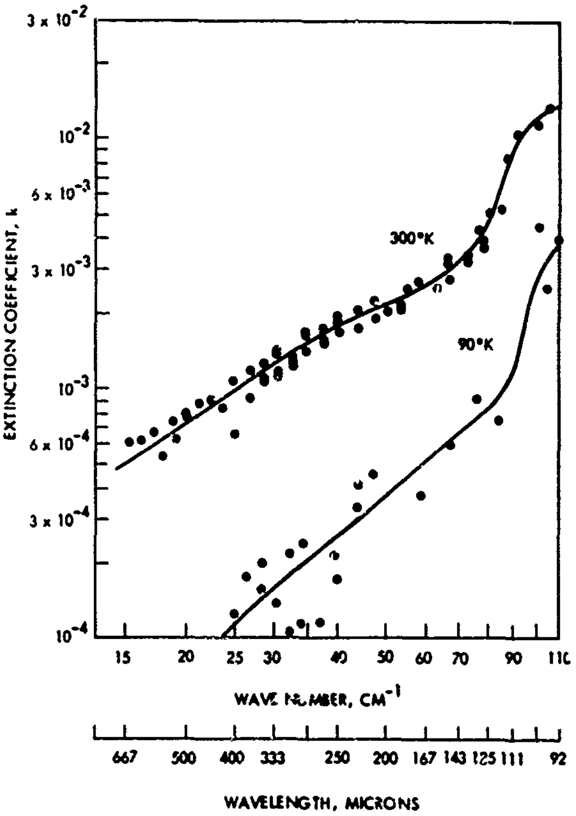


Figure 7-46

CHAPTER 8
REFRACTIVE INDEX DATA FOR METALS

INTRODUCTION

This Chapter treats the optical properties of metal films comprising the metals aluminum, gold and silver. The optical behavior of metal films is dependent on film structure, and the latter is influenced by the conditions under which the film was formed. Most of the optical metal films were formed by evaporation in a vacuum of the order of 10^{-5} torr and, at this pressure, the residual gas atoms are sufficiently abundant to affect the film properties. Owing to the chemical inertness of gold, films of this metal should not be influenced by the presence of gases during evaporation to the same extent as aluminum and silver. In some cases a more volatile eutectic alloy may be formed between the crucible (or boat) and the metal to be evaporated, resulting in the deposition of an alloy rather than the pure metal. The crystallinity of the film is dependent on the deposition rate and substrate conditions, including type of material, orientation and temperature. Annealing conditions frequently are not detailed sufficiently to ascertain whether the film is amorphous or crystalline. The optical constants of metal films show a dependence on film thickness and often the latter either is not reported or not uniform. It should be apparent from the foregoing discussion that agreement on optical constants of metal films among various observers may be too much to hope for and, indeed, such is the case.

The data permit some generalizations which apply to all three metals. Extinction coefficients tend to show less spread among observers; this is attributed by Schulz & Tangherlini (27635) to the condition that k is dependent on the density of free electrons in the metal, and this density is probably independent of structure defects. The same authors explain the greater variation in the refractive index (n) on its dependence on the conductivity of the metal, which is highly sensitive to the presence of defects and strains.

DATA SUMMARY

Table 8-1 lists all data presentations for aluminum, gold and silver. Figures 8-1 and Tables 8-2 to 8-8 provide aluminum data and the lowering in refractive index by an amorphous-crystalline transformation is observed (Tables 8-2 versus 8-7); data for the polycrystalline film resemble bulk data and this is not unexpected as the density of polycrystalline film approaches that of bulk material, while amorphous aluminum has a much lower density [Motulevich, et al. (25734)].

Gold data are covered in Figures 8-2 to 8-6 and Tables 8-9 to 8-20. Particularly interesting is Figure 8-3 which shows a reduction in refractive index as a result of annealing. Table 8-11 shows the great reduction which may occur in refractive index as the film thickness approaches bulk levels. Similarly, an increase in extinction coefficient is noted as the film thickness is increased (Table 8-12). Data for silver are presented in Figures 8-7 to 8-14 and Tables 8-21 to 8-31. Refractive index and extinction coefficient values have been calculated for a wide temperature range and are included as Figures 8-13 and 8-14.

Table 8-1. List of Metal Data

Metal	Figure	Table	n, k	Form	Crystal	Wavelength, (Microns) From	To	Remarks	Parameter
Aluminum		8-2	n, k	Film	Amorphous	0.96	1.82		Wavelength
Aluminum		8-3	n, k		Amorphous	2	12		Wavelength
Aluminum	8-1		n		*	0.4	0.95	Annealed film	Wavelength
Aluminum		8-4	n, k		*	0.4	0.95	Annealed film (n)	Wavelength
Aluminum		8-5	n, k		*	0.8	9.0		Wavelength
Aluminum		8-6	n		*	0.4	2.0		Wavelength
Aluminum		8-7	n, k		Polycryst	1.0	1.0		Wavelength
Aluminum		8-8	n, k		*	0.8	9.0		Temperature
Gold		8-9	n		Polycryst	1	12	Annealed film	Wavelength
Gold		8-10	n, k		*	0.4	0.95	Annealed film (n)	Wavelength
Gold	8-2		n		*	0.4	0.95	Annealed film	Wavelength
Gold		8-11	n		*	0.8	1.1		Wavelength
Gold		8-12	k		*	0.8	2.0		Wavelength
Gold	8-3		n		*	0.4	2.5	Annealed and unannealed film	Wavelength
Gold		8-13	n, k		*	0.8	1.0		Wavelength
Gold		8-14	n, k		*	0.8	1.0		Wavelength
Gold		8-15	n, k		*	1.25	1.0		Wavelength
Gold	8-4		n		*	1.3	12.1		Wavelength
Gold		8-16	n		*	1.3	12.1		Wavelength
Gold	8-5		n		*	1	12	82°K, 295°K	Wavelength
Gold		8-17	n		*	1	11	82°K, 295°K	Wavelength
Gold		8-18	n		*	0.8	1.1		Film Thickness
Gold		8-19	k		*	0.8	2.0		Film Thickness
Gold	8-6		n		*	1	12	82°K, 295°K	Temperature
Gold		8-20	n		*	1	11	82°K, 295°K	Temperature
Silver	8-7		n		*	0.5	1.5		Wavelength
Silver		8-21	n, k		*	0.8	1.0		Wavelength
Silver	8-8		n		*	0.4	1.0		Wavelength
Silver	8-9		k		*	0.4	1.0		Wavelength
Silver	8-10		n		*	0.4	0.95	Annealed film	Wavelength
Silver		8-22	n, k		*	0.4	0.95	Annealed film (n)	Wavelength
Silver		8-23	n, k		*	0.8	1.0		Wavelength
Silver		8-24	n, k		*	1.25	10		Wavelength
Silver		8-25	n		*	0.8	1.0		Wavelength
Silver		8-26	k		*	0.8	1.5		Wavelength
Silver	8-11		n		*	1	12	82°K, 295°K	Wavelength
Silver		8-27	n		*	1	12	82°K, 295°K	Wavelength
Silver	8-12	n, k	n		*	0.3	100	300-1200°K	Wavelength
Silver		8-28	n, k		*	1.0	6.0	n-type	Wavelength
Silver		8-29	n		*	0.8	1.0		Film Thickness
Silver		8-30	k		*	0.8	1.5		Film Thickness
Silver	8-13		n		*	1	12	82°K, 295°K	Temperature
Silver		8-31	n'		*	1	12	82°K, 295°K	Temperature
Silver	8-14		n, k		*	0.3	100	300-1200°K	Temperature

*Not stated.

PARAMETER: Wavelength

MATERIAL: Aluminum

Wavelength, (Microns)	Refractive Index, n	Extinction Coefficient, k
0.96	2.0	10.2
1.15	1.8	12.0
1.46	3.1	16.4
1.82	4.9	19.9

FORM Film-Amorphous

THICKNESS Not stated mm

RAY ORDINARY ☒, EXTRAORDINARY ☐

WAVELENGTH 0.96-1.82 μ

TEMPERATURE ~298 °K

METHOD Reflection

REFERENCE Motulevich, et al. (25734)

REMARKS Film deposited on glass, resulting in sample of mean density of 2.2 $g \cdot cm^{-3}$

Table 8-2

Wavelength, (Microns)	Refractive Index, n	Extinction Coefficient, k
2.0	2.30	16.5
2.5	3.22	20.3
3.0	4.41	24.2
4.0	5.97	30.3
5.0	8.19	36.8
6.0	11.00	42.4
7.0	14.63	49.0
8.0	17.00	55.0
9.0	21.1	61.3
10.0	25.4	67.3
11.0	28.3	71.1
12.0	33.6	76.4

THICKNESS 1.5×10^{-4} mm

RAY ORDINARY ☒, EXTRAORDINARY ☐

WAVELENGTH 2 - 12 μ

TEMPERATURE 298 °K

METHOD Reflection

REFERENCE Beattie [1955]

REMARKS Specimens evaporated onto glass substrate at ~ 10^{-5} torr pressure.

Table 8-3

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PARAMETER: Wavelength

MATERIAL: Aluminum

FORM Film

THICKNESS 1.5×10^{-4} (n); 5×10^{-5} (k) mm

RAY ORDINARY ☒ EXTRAORDINARY ☐

WAVELENGTH 0.4 - 0.95 μ

TEMPERATURE ~298 °K

METHOD Reflection (n); Interference (k).

REFERENCE Schulz Tangherlin (27635) for n; Schulz (27634) for k.

REMARKS Evaporation from tungsten wire at 10^{-5} Torr onto glass substrate for n and mica substrate for k.

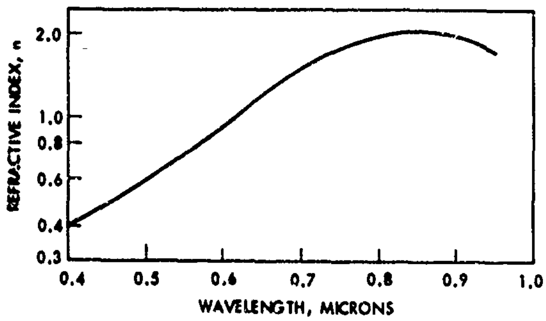

Figure 8-1

Wavelength, (Microns)	Refractive Index, n	Extinction Coefficient, k
0.40	0.40	3.92
0.45	0.49	4.32
0.50	0.62	4.80
0.55	0.76	5.32
0.60	0.97	6.00
0.65	1.24	6.60
0.70	1.55	7.00
0.75	1.80	7.12
0.80	1.99	7.05
0.85	2.08	7.15
0.90	1.96	7.70
0.95	1.75	8.50

Table 8-4

PARAMETER: Wavelength

MATERIAL: Aluminum

Wavelength, (Microns)	Refractive Index, n		Extinction Coefficient, k	
	78°K	295°K	78°K	295°K
0.8	0.83	1.12	6.0	6.0
0.9	0.75	1.05	7.0	7.0
1.2	0.63	0.95	9.6	9.6
1.5	0.78	1.14	12.1	12.1
2.0	1.30	1.75	16.1	16.1
2.5	1.7	2.4	19.8	19.8
3.0	2.2	3.2	23.5	23.5
4.0	3.2	4.8	30.1	30.0
5.0	4.4	6.7	37.8	37.6
6.0	6.5	9.5	44.9	44.4
7.0		12.6	52.0	49.0
8.0		15.6		55.0
9.0		21.1		61.3

FORM Film

THICKNESS 1.5×10^{-5} mm

RAY ORDINARY ☒, EXTRAORDINARY ☐

WAVELENGTH 0.8 - 9.0 μ

TEMPERATURE 78, 295 °K

METHOD Reflection

REFERENCE Golovashkin, et al. (14298)

REMARKS Film formed by vacuum evaporation from tungsten helix onto glass.

Table 8-5

Wavelength, (Microns)	Refractive Index, n
0.40	0.32
0.70	1.26
0.75	1.50
0.80	1.78
0.85	1.91
0.875	1.82
0.90	1.70
0.95	1.40
1.00	1.17
1.10	0.85
1.20	0.78
1.50	1.00
1.70	1.31
2.00	1.74

THICKNESS Not Stated mm

RAY ORDINARY ☒, EXTRAORDINARY ☐

WAVELENGTH 0.40 - 2.00 μ

TEMPERATURE 298 °K

METHOD Reflection

REFERENCE Shlkyarevskii and Yarovaya (19998)

REMARKS Evaporation at 2×10^{-5} torr onto glass substrate

Table 8-6

PARAMETER: Wavelength

MATERIAL: Aluminum

Wavelength, (Microns)	Refractive Index, n	Extinction Coefficient, k
1.00	0.98	7.65
1.50	1.14	11.6
2.00	1.67	15.2
2.50	2.50	18.8
3.00	3.48	22.6
4.00	5.58	29.4
5.00	7.84	35.7
6.00	10.4	41.3
8.00	16.2	52.2
10.0	25.5	60.9

FORM Film - Polycrystalline

THICKNESS Not Stated mm

RAY ORDINARY ☒, EXTRAORDINARY ☐

WAVELENGTH 1 - 10 μ

TEMPERATURE ~298 °K

METHOD Reflection

REFERENCE Motulevich, et al. (25734)

REMARKS Film deposited on glass, resulting in sample density of 2.7 g cm^{-3}.

Table 8-7

PARAMETER: Temperature

MATERIAL: Aluminum

Wavelength, Microns	Refractive Index, n		Extinction Coefficient, k	
	78°K	295°K	78°K	295°K
0.8	0.83	1.12	6.0	6.0
0.9	0.75	1.05	7.0	7.0
1.2	0.63	0.95	9.6	9.6
1.5	0.78	0.14	12.1	12.1
2.0	1.30	1.75	16.1	16.1
2.5	1.7	2.4	19.8	19.8
3.0	2.2	3.2	23.5	23.5
4.0	3.2	4.8	30.1	30.0
5.0	4.4	6.7	37.8	37.6
6.0	6.5	9.5	44.9	44.4
7.0		12.6	52.0	49.0
8.0		15.6		55.0
9.0		21.1		61.3

FORM Film

THICKNESS 1.5×10^{-5} mm

RAY ORDINARY ☒, EXTRAORDINARY ☐

WAVELENGTH 0.8 - 9.0 μ

TEMPERATURE 78, 295 °K

METHOD Reflection

REFERENCE Golovashkin, et al. (14298)

REMARKS Film formed by vacuum evaporation from tungsten helix onto glass.

Table 8-8

PARAMETER: Wavelength

MATERIAL: Gold

Wavelength, Microns	Refractive Index, n	Extinction Coefficient, k
1.0	0.224	6.71
1.5	0.357	10.4
2.0	0.546	13.9
2.5	0.82	17.3
3.0	1.17	21.0
4.0	2.04	27.9
5.0	3.27	35.2
6.0	4.70	41.7
8.0	7.82	54.6
10.0	11.5	67.5
12.0	15.4	80.5

FORM Film - Polycrystalline

THICKNESS $(0.5 - 1) \times 10^{-3}$ mm

RAY ORDINARY ☒, EXTRAORDINARY ☐

WAVELENGTH 1 - 12 μ

TEMPERATURE ~298 °K

METHOD Reflection

REFERENCE Motulevich & Shubin (19922)

REMARKS Evaporation at 3×10^{-6} torr pressure from tungsten onto glass substrate, followed by anneal of at least three hours at 10^{-6} torr and 673°K.

Table 8-9

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PARAMETER: Wavelength

MATERIAL: Gold

Wavelength, (Microns)	Refractive Index, n	Extinction Coefficient, k
0.40	1.45	
0.45	1.40	1.86
0.50	0.84	1.84
0.55	0.34	2.37
0.60	0.23	2.97
0.65	0.19	3.50
0.70	0.17	3.97
0.75	0.16	4.42
0.80	0.16	4.84
0.85	0.17	5.30
0.90	0.18	5.72
0.95	0.19	6.10

FORM Film

THICKNESS $(1.5\text{-}2) \times 10^{-4}$ mm

RAY ORDINARY ☒, EXTRAORDINARY ☐

WAVELENGTH 0.4 - 0.95 μ

TEMPERATURE ~298 °K

METHOD Reflection (n); Interference (k).

REFERENCE Schulz & Tangherline (27635) for n, Schulz (27634) for k.

REMARKS Evaporation from tungsten wire at 10^{-5} torr onto glass substrate for n and mica substrate for k. Glass substrate sample annealed at <403° K

Table 8-10

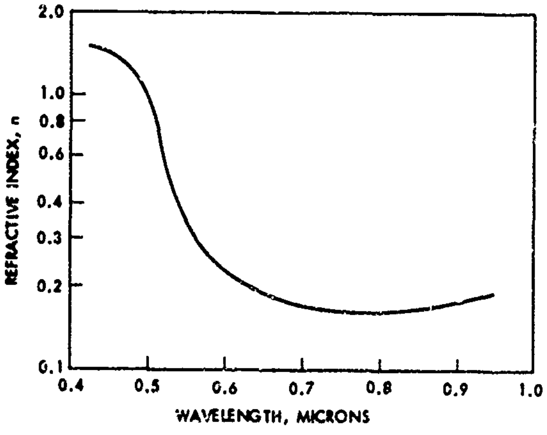


Figure 8-2

PARAMETER: Wavelength

MATERIAL: Gold

FORM Film

THICKNESS 1×10^{-6} to bulk mm

RAY ORDINARY ☒, EXTRAORDINARY ☐

WAVELENGTH 0.8 - 1.1 μ

TEMPERATURE ~298 °K

METHOD Miscellaneous

REFERENCE Mayer [1950]

REMARKS Compilation of older data

Table 8-11

Film Thickness, Å	Refractive Index, n @ Wavelength Microns 0.8	0.9	1.0	1.1	Observer
10	4.35	4.5	4.85	5.05	Goos [1937]
20	5.25	5.1	5.0	5.0	Goos [1937]
30	5.05	5.15	5.0	5.0	Goos [1937]
40	4.15	4.7	4.9	5.15	Goos [1937]
50	4.3	4.55	4.9	5.15	Goos [1937]
75	4.3	4.6	4.75	5.15	Goos [1937]
100	3.5	3.95	4.35	4.85	Goos [1937]
150	1.4	1.8	2.15	2.55*	Goos [1937]
200	0.45	0.5	0.55	0.6	Goos [1937]
400	0.18	0.19	0.195		Kretzmann (40353)
∞	0.2	0.25	0.25	0.3	Pogany [1916]

*Thickness range 100-400 Å

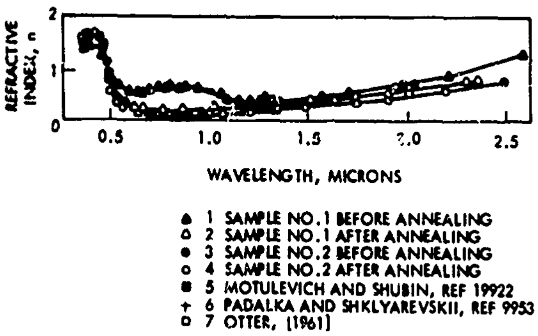
Table 8-12

Film Thickness, Å	Extinction Coefficient, k @ Wavelength Microns 0.8	0.9	1.0	1.1	1.5	2.0	Observer
10	0.7	0.5	0.25	0.05			Goos [1937]
20	1.65	1.1	0.7	0.35			Goos [1937]
30	2.75	1.75	1.25	0.8			Goos [1937]
40	2.9	2.3	1.95	1.3			Goos [1937]
50	3.3	2.8	2.6	2.0			Goos [1937]
75	4.1	3.75	3.6	5.3			Goos [1937]
100	4.55	4.5	4.4	4.4			Goos [1937]
	5.56*						Haringhuizen, et al. [1937]
150	5.0	5.45	5.8	6.4			Goos [1937]
200	5.2	5.9	6.7	7.5			Goos [1937]
500-1000	5.19		6.9		11.3	15.4	Hagen & Rubens [1902]
∞	5.2	6.0	6.95	7.65			Goos [1937]
	4.2	4.93	5.57				Statescu [1910]

*Thickness range 100-400 Å

PARAMETER: Wavelength

MATERIAL: Gold



FORM Film

THICKNESS Not stated mm

RAY ORDINARY ☒, EXTRAORDINARY ☐

WAVELENGTH 0.4 - 2.5 μ

TEMPERATURE ~298 °K

METHOD Reflection

REFERENCE Shklyarevskii & Yarovaya (27261)

REMARKS Deposition rates: Sample No. 1- one Å sec^{-1}, sample No. 2- 100 Å sec^{-1}. Samples annealed at 393° K in vacuo after deposition, where stated.

Figure 8-3

Wavelength, (Microns)	Refractive Index, n	Extinction Coefficient, k
0.800	0.178	4.20
0.850	0.182	4.53
0.900	0.190	4.93
0.950	0.199	5.27
1.000	0.194	5.57

THICKNESS 0.33 mm

RAY ORDINARY ☒, EXTRAORDINARY ☐

WAVELENGTH 0.80 - 1.0 μ

TEMPERATURE ~298 °K

METHOD Reflection

REFERENCE Kretzmann (40353)

REMARKS Evaporation from tungsten or molybdenum crucibles at <1 x 10^{-4} torr.

Table 8-13

PARAMETER: Wavelength

MATERIAL: Gold

Wavelength, (Microns)	Refractive Index, n	Extinction Coefficient, k
0.800	0.149	4.654
0.850	0.157	4.993
0.900	0.166	5.335
0.950	0.174	5.691
1.000	0.179	6.044

FORM Film

THICKNESS 0.3 - 0.4 mm

RAY ORDINARY ☒, EXTRAORDINARY ☐

WAVELENGTH 0.8 - 1.0 μ

TEMPERATURE ~298 °K

METHOD Reflection

REFERENCE Weiss (6107)

REMARKS Evaporation onto silica substrate at 2×10^{-5} torr pressure

Table 8-14

Wavelength, (Microns)	Refractive Index, n	Extinction Coefficient, k
1.25	0.38	8.0
1.5	0.53	9.5
2	0.85	12.6
3	1.64	18.6
4	2.6	24.6
5	3.8	30.7
6	5.1	36.4
7	6.8	41.6
8	8.5	46.4
9	10.5	50.8
10	12.4	55.0

THICKNESS Not stated mm

RAY ORDINARY ☒, EXTRAORDINARY ☐

WAVELENGTH 1.25 - 10 μ

TEMPERATURE 293 °K

METHOD Reflection

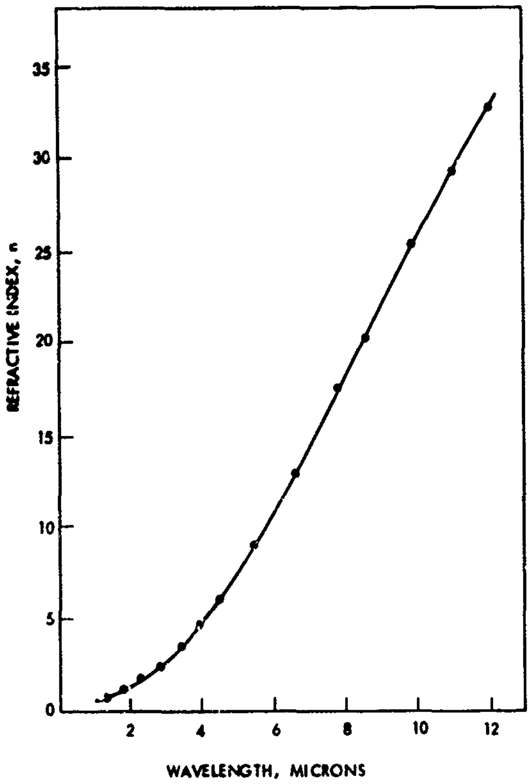
REFERENCE Dold & Mecke (27079)

REMARKS Evaporation from tantalum crucible.

Table 8-15

PARAMETER: Wavelength

MATERIAL: Gold



FORM Film

THICKNESS (1.5 - 2) x 10^{-3} mm

RAY ORDINARY ☒ EXTRAORDINARY ☐

WAVELENGTH 1 - 12 μ

TEMPERATURE ~298 °K

METHOD Reflection

REFERENCE Shkliarevskii & Padalka (36056)

REMARKS Vacuum evaporation from molybdenum crucible onto glass substrate. According to the authors, samples may have been insufficiently clean, resulting in high refractive indices.

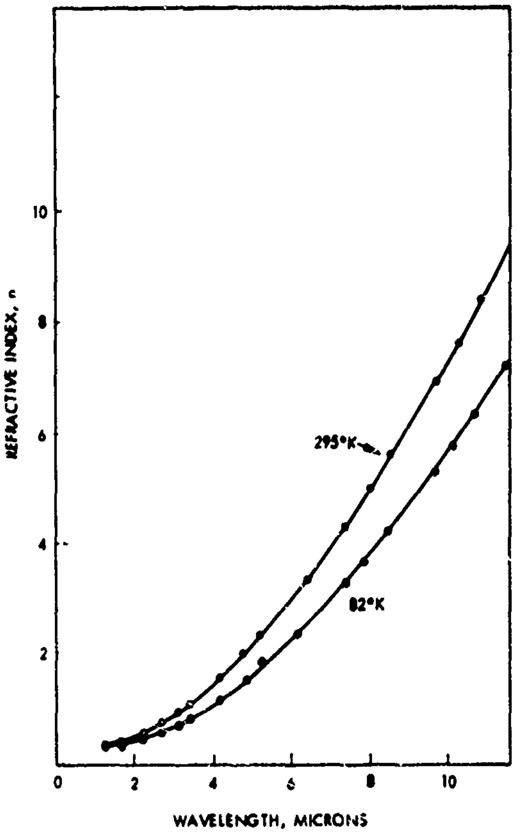
Figure 8-4

Wavelength (Microns)	Refractive Index, n
1.3	0.69
1.75	1.1
1.95	1.3
2.26	1.62
2.8	2.2
3.43	3.49
3.95	4.71
4.55	5.95
5.5	9.05
6.65	12.9
7.9	17.6
8.65	20.2
9.9	25.2
11.1	29.0
12.1	32.4

Table 8-16

PARAMETER: Wavelength

MATERIAL: Gold



FORM Film

THICKNESS Not stated mm

RAY ORDINARY ☒ , EXTRAORDINARY ☐

WAVELENGTH 1 - 12 μ

TEMPERATURE 82, 295 °K

METHOD Reflection

REFERENCE Padalka & Shklyarevskii (9953)

REMARKS Evaporation from tantalum crucible onto glass substrate at ~10^{-5} torr pressure.

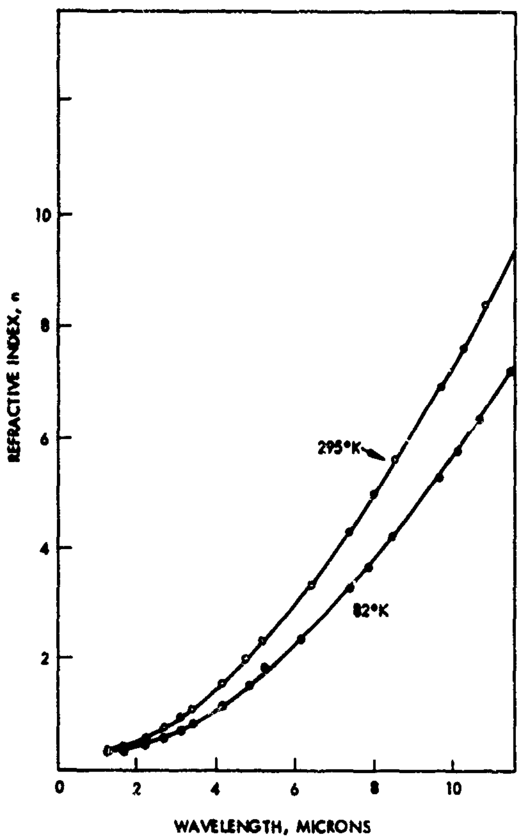
Figure 8-5

Wavelength, (Microns)	Refractive Index, n	
	T = 295°K	T = 82°K
λ (μ)	n	n
1	0.31	0.28
2	0.54	0.45
3	0.93	0.74
4	1.49	1.15
5	2.19	1.67
6	3.01	2.29
7	3.97	2.99
8	5.05	3.84
9	6.21	4.74
10	7.41	5.70
11	8.71	6.76

Table 8-17

PARAMETER: Temperature

MATERIAL: Gold



FORM Film

THICKNESS Not stated mm

RAY ORDINARY ☒ , EXTRAORDINARY ☐

WAVELENGTH 1 - 12 μ

TEMPERATURE 82, 295 °K

METHOD Reflection

REFERENCE Padalka & Shklyarevskii (9953)

REMARKS Evaporation from tantalum crucible onto glass substrate at 10^{-5} torr pressure.

Figure 8-6

PARAMETER: Film Thickness

MATERIAL: Gold

Film Thickness Å	Refractive Index, n @ Wavelength, Microns 0.8	0.9	1.0	1.1	Observer
10	4.35	4.5	4.95	5.05	Goos [1937]
20	5.25	5.1	5.0	5.0	Goos [1937]
30	5.05	5.15	5.0	5.0	Goos [1937]
40	4.15	4.7	4.9	5.15	Goos [1937]
50	4.3	4.55	4.9	5.15	Goos [1937]
75	4.3	4.6	4.75	5.15	Goos [1937]
100	3.5	3.95	4.35	4.85	Goos [1937]
150	1.4	1.8	2.15	2.55*	Goos [1937]
200	0.45	0.5	0.55	0.6	Goos [1937]
400	0.18	0.19	0.195		Kretzmann (40353)
∞	0.2	0.25	0.25	0.3	Pogany [1916]

*Thickness range 100-400 A

FORM Film

THICKNESS 1×10^{-6} to bulk mm

RAY ORDINARY ☑, EXTRAORDINARY ☐

WAVELENGTH 0.8 - 1.1 μ

TEMPERATURE ~298 °K

METHOD Miscellaneous

REFERENCE Mayer [1950]

REMARKS Compilation of older data

Table 8-18

Film Thickness, Å	Extinction Coefficient, k @ Wavelength, Microns 0.8	0.9	1.0	1.1	1.[illegible]	2.0	Observer
10	0.7	0.5	0.25	[illegible]			Goos [1937]
20	1.[illegible]5	1.1	0.7	0.35			Goos [1937]
30	2.75	[illegible].75	1.25	0.8			Goos [1937]
40	2.9	2.3	1.95	1.3			Goos [1937]
50	3.3	2.8	2.6	2.0			Goos [1937]
[illegible]	4.1	[illegible].75	3.[illegible]	[illegible]			Goos [1937]
100	4.55	4.5	4.4	4.4			Goos [1937]
	[illegible]*				—		Haringhuizen, et al. [1937]
150	5.0	5.45	5.8	6.4			Goos [1937]
200	5.2	5.9	6.7	7.5	—		Goos [1937]
[illegible]	5.1[illegible]		[illegible]		11.3	15.4	Hagen & Rubens [1902]
∞	5.2	6.0	6.95	7.65			Goos [1937]
	4.2	4.9[illegible]	5.57				Statescu [1910]

*Thickness range 100-400 Å

Table 8-19

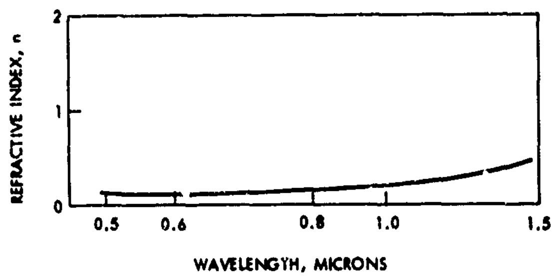
TABLE 8-20

Not included in this report.
We will not receive this table.

M. Anderson
DDC-TCA
13 May 70

PARAMETER: Wavelength

MATERIAL: Silver



FORM Film

THICKNESS Not stated mm

RAY ORDINARY ☒ EXTRAORDINARY ☐

WAVELENGTH 0.5 - 1.5 μ

TEMPERATURE ~298 °K

METHOD Reflection

REFERENCE Yarovaya & Shklyarevskii (36165)

REMARKS Samples identical to Ref. 9953.

Figure 8-7

Wavelength, (Microns)	Refractive Index, n	Extinction Coefficient, k
0.800	0.196	5.54
0.850	0.200	5.87
0.900	0.227	6.26
0.950	0.245	6.61
1.000	0.263	6.93

THICKNESS 0.17 mm

RAY ORDINARY ☒, EXTRAORDINARY ☐

WAVELENGTH 0.8 - 1.0 μ

TEMPERATURE ~298 °K

METHOD Reflection

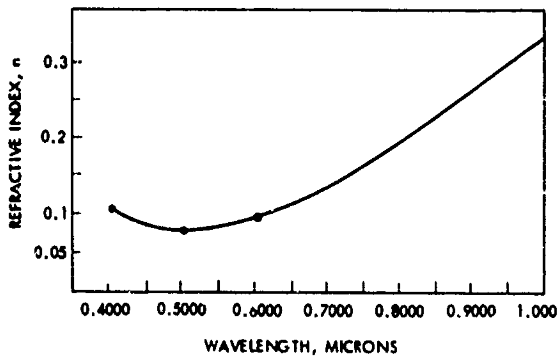
REFERENCE Kretzmann (40353)

REMARKS Evaporation from tungsten or molybdenum crucible at <1 x 10^{-4} torr pressure.

Table 8-21

PARAMETER: Wavelength

MATERIAL: Silver



FORM Film

THICKNESS $>0.7 \times 10^{-4}$ mm

RAY ORDINARY ☒ , EXTRAORDINARY ☐

WAVELENGTH 0.4 - 1.0 μ

TEMPERATURE ~298 °K

METHOD Reflection, Transmission

REFERENCE Idczak [1967]

REMARKS Film prepared by evaporation onto glass substrate at $\sim 10^{-4}$ torr.

Figure 8-8

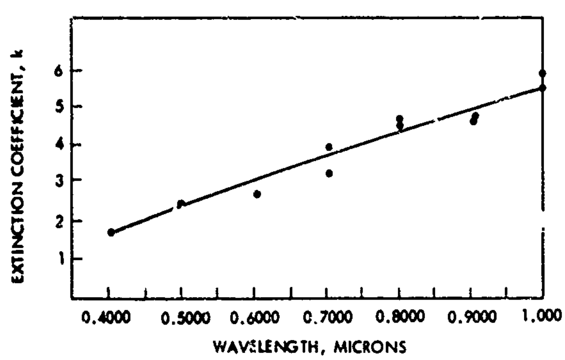


Figure 8-9

PARAMETER: Wavelength

MATERIAL: Silver

FORM Film

THICKNESS 1.5×10^{-4} for n, 5×10^{-5} for k mm

RAY ORDINARY ☒, EXTRAORDINARY ☐

WAVELENGTH 0.4 - 0.95 μ

TEMPERATURE ~298 °K

METHOD Reflection (n); Interference (k)

REFERENCE Schulz & Tangherlini (27635) for n, Schulz (27634) for k.

REMARKS Evaporation from molybdenum crucible at $\sim 10^{-5}$ torr onto glass substrate for n, mica substrate for k.

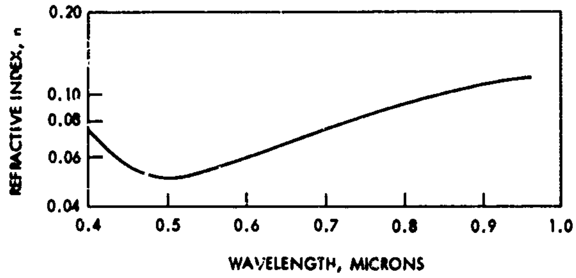


Figure 8-10

Wavelength, (Microns)	Refractive Index, n	Extinction Coefficient, k
0.40	0.075	1.93
0.45	0.055	2.42
0.50	0.050	2.87
0.55	0.055	3.32
0.60	0.060	3.75
0.65	0.070	4.20
0.70	0.075	4.62
0.75	0.080	5.05
0.80	0.090	5.45
0.85	0.100	5.85
0.90	0.105	6.22
0.95	0.110	6.56

Table 8-22

PARAMETER: Wavelength

MATERIAL: Silver

Wavelength, (Microns)	Refractive Index, n	Extinction Coefficient, k
0.800	0.110	5.409
0.850	0.121	5.757
0.900	0.128	6.089
0.950	0.130	6.476
1.000	0.129	6.829

FORM Film

THICKNESS 0.12 - 0.20 mm

RAY ORDINARY ☒, EXTRAORDINARY ☐

WAVELENGTH 0.8 - 1.00 μ

TEMPERATURE ~298 °K

METHOD Reflection

REFERENCE Weiss (6107)

REMARKS Evaporation from tungsten or molybdenum crucible onto silica substrate at 2 x 10^{-5} torr.

Table 8-23

Wavelength, (Microns)	Refractive Index, n	Extinction Coefficient, k
1.25	0.37	7.7
1.5	0.45	9.0
2	0.65	12.2
3	1.30	18.2
4	2.3	24.3
5	3.5	30.4
6	5.0	36.0
7	6.9	41.0
8	8.9	46.0
9	11.0	50.0
10	13.3	54.0

THICKNESS Not stated mm

RAY ORDINARY ☒, EXTRAORDINARY ☐

WAVELENGTH 1.25 - 10 μ

TEMPERATURE 293 °K

METHOD Reflection

REFERENCE Dold & Mecke (27079)

REMARKS Evaporation from molybdenum crucible.

Table 8-24

PARAMETER: Wavelength

MATERIAL: Silver

FORM Film

THICKNESS 0.75×10^{-6} to bulk mm

RAY ORDINARY ☒ , EXTRAORDINARY ☐

WAVELENGTH 0.8 - 1.0 μ

TEMPERATURE ~298 °K

METHOD Misc.

REFERENCE Mayer [1950]

REMARKS Compilation of older data

Table 8-25

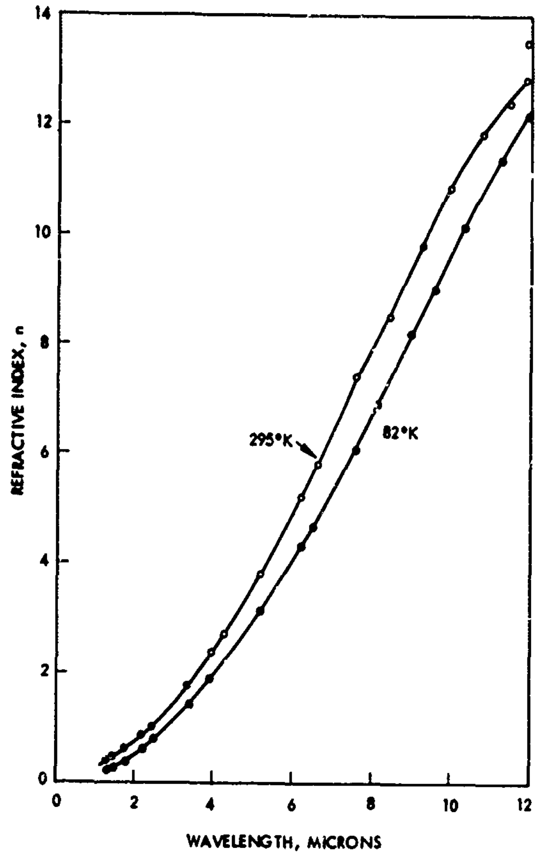
Film Thickness, Å	Refractive Index, n @ Microns Wavelength			Observer
	0.8	0.9	1.0	
7.5	2.5	2.2		Murmann [1936]
10	2.95	3.05		Krautkraemer [1938]
15	2.3	2.6		Murmann [1936]
20	0.6	1.0		Murmann [1936]
∞	0.20	0.23	0.26	Kretzmann [1940]

Table 8-26

Film Thickness, Å	Extinction Coefficient, k @ Microns Wavelength				Observer
	0.8	0.9	1.0	1.5	
7.5	5.15	5.2			Murmann [1936]
10	4.9	5.0			Murmann [1936]
15	5.1	5.35			Murmann [1936]
20	5.5	5.8			Murmann [1936]
500	6.21		8.00	12.4	Hagen & Rubens [1902]
∞	5.54	6.25	6.93		Kretzmann [1940]

PARAMETER: Wavelength

MATERIAL: Silver



FORM: Film

THICKNESS: Not stated mm

RAY: ORDINARY ☒, EXTRAORDINARY ☐

WAVELENGTH: 1 - 12 μ

TEMPERATURE: 82, 295 °K

METHOD: Reflection

REFERENCE: Padalka & Shklyarevskii (9953)

REMARKS: Evaporation from tantalum crucible onto glass substrate at 10^{-5} torr

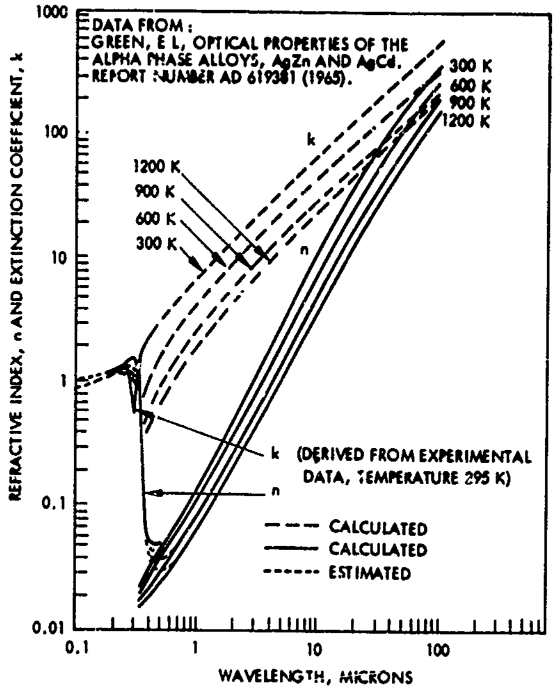
Figure 8-11

Wavelength, (Microns)	Refractive Index, n	
	T = 295°K	T = 82°K
1	0.25	0.22
2	0.68	0.57
3	1.38	1.14
4	2.34	1.92
5	3.52	2.88
6	4.87	4.02
7	6.31	5.31
8	7.86	6.70
9	9.36	8.10
10	10.8	9.60
11	12.0	10.9
12	12.8	--

Table 8-27

PARAMETER: Wavelength

MATERIAL: Silver



FORM Not stated

THICKNESS Not stated mm

RAY ORDINARY ☒, EXTRAORDINARY ☐

WAVELENGTH 0.3 - 100 μ

TEMPERATURE 300 - 1200 °K

METHOD NA

REFERENCE Grenis (30490)

REMARKS Calculated results, based on optical, conductivity and dielectric measurements.

Figure 8-12

Wavelength, (Microns)	Refractive Index, n	Extinction Coefficient, k
1.03	0.27	7.00
1.28	0.36	8.58
1.71	0.53	11.7
2.50	0.91	17.2
3.48	1.65	23.75
4.38	2.0	29.65
5.38	2.9	36.9
6.00	4.3	40.65

THICKNESS Not stated-Mirror mm

RAY ORDINARY ☒, EXTRAORDINARY ☐

WAVELENGTH 1 - 6 μ

TEMPERATURE ~298 °K

METHOD Reflection

REFERENCE Motulevich (40051)

REMARKS n-type, carrier concentration = 5.2×10^{2} cm^{-3}

Table 8-28

PARAMETER: Film Thickness

MATERIAL: Silver

FORM Film

THICKNESS 0.75×10^{-6} to bulk mm

RAY ORDINARY ☒ , EXTRAORDINARY ☐

WAVELENGTH 0.8 - 1.0 μ

TEMPERATURE ~298 °K

METHOD Misc.

REFERENCE Mayer [1950]

REMARKS Compilation of older data

Table 8-29

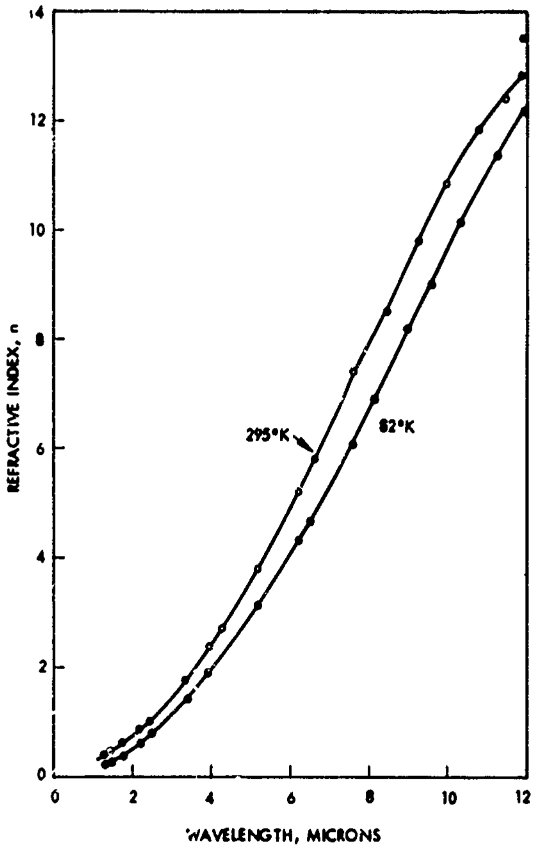
Film Thickness, Å	Refractive Index, n @ Microns Wavelength			Observer
	0.8	0.9	1.0	
7.5	2.5	2.2		Murmann [1936]
10	2.95	3.05		Krautkraemer [1938]
15	2.3	2.6		Murmann [1936]
20	0.6	1.0		Murmann [1936]
∞	0.20	0.23	0.26	Kretzmann [1940]

Table 8-30

Film Thickness, Å	Extinction Coefficient, k @ Microns Wavelength				Observer
	0.8	0.9	1.0	1.5	
7.5	5.15	5.2			Murmann [1936]
10	4.9	5.0			Murmann [1936]
15	5.1	5.35			Murmann [1936]
20	5.5	5.8			Murmann [1936]
500	6.21		8.00	12.4	Hagen & Rubens [1902]
∞	5.54	6.25	6.93		Kretzmann [1940]

PARAMETER: Temperature

MATERIAL: Silver



FORM Film

THICKNESS Not stated mm

RAY ORDINARY ☒ , EXTRAORDINARY ☐

WAVELENGTH 1 - 12 μ

TEMPERATURE 82, 295 °K

METHOD Reflection

REFERENCE Padalka & Shklyarevskii (9953)

REMARKS Evaporation from tantalum crucible onto glass substrate at 10^{-5} torr

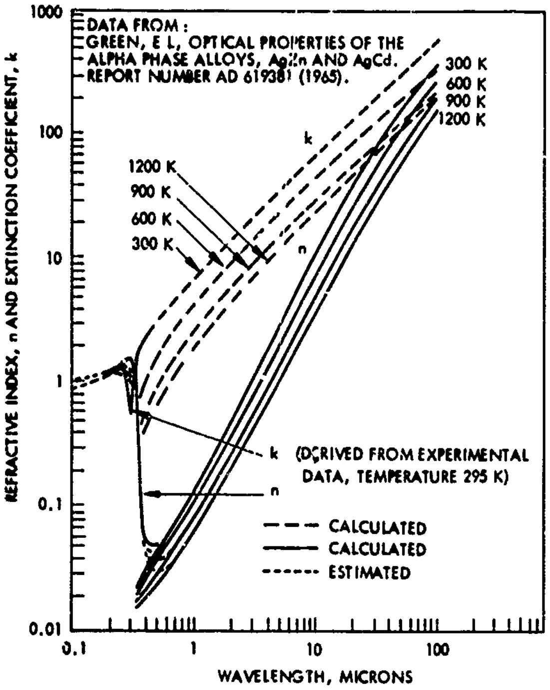
Figure 8-13

Wavelength, Micron	Refractive Index, n	
	T = 295°K	T = 82°K
1	0.25	0.22
2	0.68	0.57
3	1.38	1.14
4	2.34	1.92
5	3.52	2.88
6	4.87	4.02
7	6.31	5.31
8	7.86	6.70
9	9.36	8.10
10	10.8	9.60
11	12.0	10.0
12	12.8	--

Table 8-31

PARAMETER: Temperature

MATERIAL: Silver



FORM Not Stated mm

THICKNESS Not Stated mm

RAY ORDINARY ☒, EXTRAORDINARY ☐

WAVELENGTH 0.3 - 100 μ

TEMPERATURE 300 - 1200 °K

METHOD NA

REFERENCE Grenis (30490)

REMARKS Calculated results, based on optical, conductivity and dielectric measurements.

Figure 8-14

CHAPTER 9
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13. ABSTRACT

Refractive index data and some extinction coefficients are provided for the infrared region for the following materials: silicon, germanium, zinc sulfide, cadmium telluride, zinc selenide, silica, calcium fluoride, magnesium fluoride, aluminum oxide, magnesium oxide, aluminum, gold and silver. The dependence of these optical constants on wavelength, temperature, crystal form, film preparation technique, radiation and other factors is included.

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14 KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Infrared Measurements Refractive index Extinction Coefficient Transmittance Silicon Germanium Zinc Sulfide Cadmium Telluride Zinc Selenide Silica (Quartz) Calcium Fluoride Magnesium Fluoride Aluminum Oxide (Sapphire) Magnesium Oxide Aluminum Gold Silver						

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